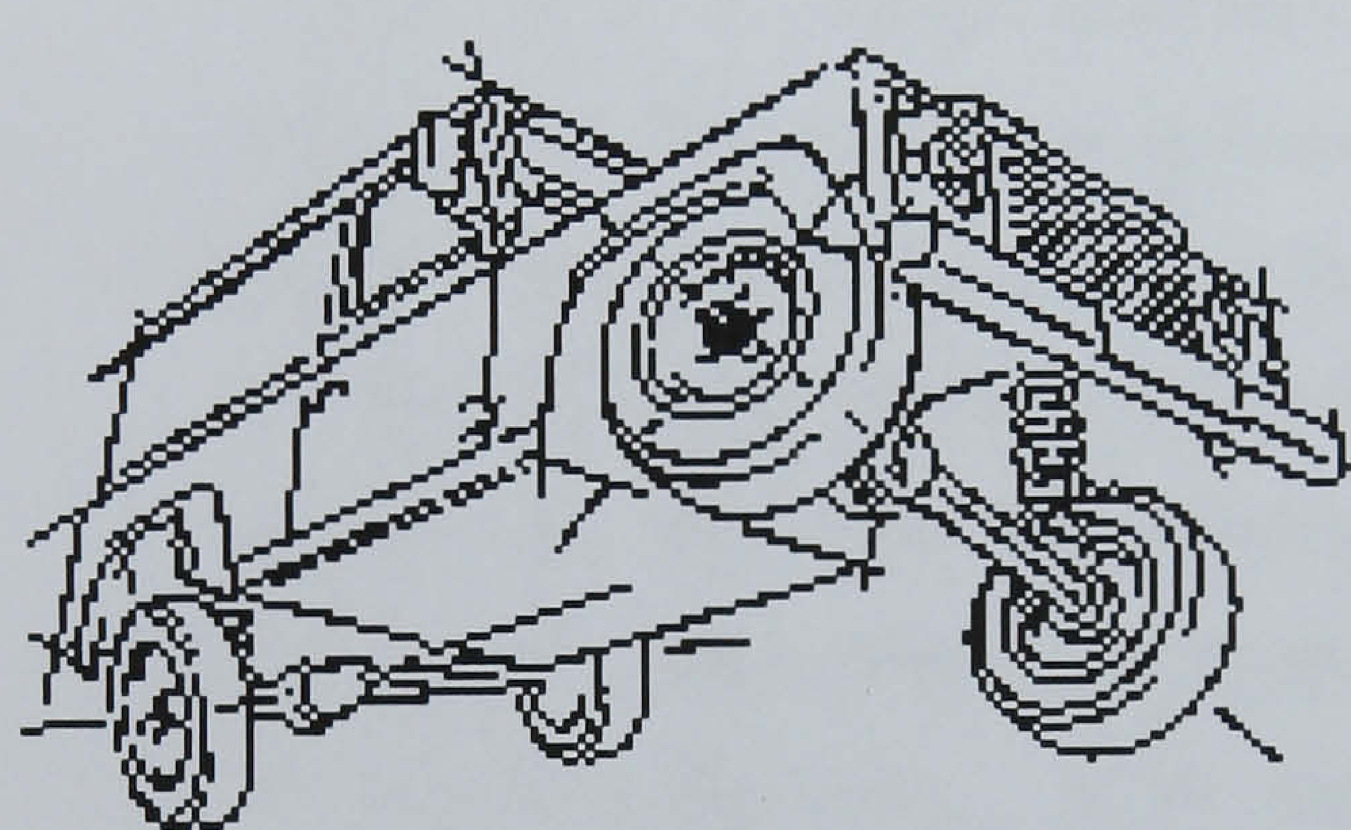
Issue 1

Executive Summary

Modelling and analysis of current and concept vehicles for the purpose of enhancing vehicle handling.



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Chassis Concepts
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Summary of the Engineering Doctorate Portfolio: July 2001

University of Warwick
Integrated Graduate Development Scheme
Engineering Doctorate Programme
EPSRC Postgraduate Studentship

Summary

In this document, research into the modelling and analysis of current and concept vehicles for the purpose of enhancing vehicle handling is summarised. This work is recounted in detail in a portfolio of reports that has been submitted for the degree of Doctor of Engineering.

The portfolio includes fifteen submissions, eleven of which are concerned with the analysis and simulation of drivers' steering behaviour. Two relate to a novel suspension concept. One addresses a current problem caused by suspension variability and one introduces a process for selecting between new suspension concepts. Each of these fifteen submissions is summarised in this document. In addition, the order in which it is recommended that these submissions be read is listed.

In section 4, a project summary of the research into the analysis and simulation of drivers' steering behaviour is presented. Existing models of drivers' steering behaviour are reviewed. Vehicle tests that illustrate the different steering styles used by different drivers are recounted. A driver model that simulates the steering behaviour exhibited in these tests is formulated. Then, this driver model is used to develop a switching strategy for variable dampers. It is demonstrated that the switching strategy enhances vehicle handling and reduces the roll experienced by drivers during a handling manoeuvre.

Finally, it is verified that this research complies with the requirement of the degree of Doctor of Engineering to demonstrate innovation in the application of knowledge to the engineering business environment. This is achieved by specifying eight examples of where new ideas and methods have been applied to address current issues within the automotive industry.

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Acknowledgements

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Declaration of Originality

Except where acknowledged, the work reported in this document is my own.

Signed

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Lucy M.T. Whittaker   4 July 2001

1 Introduction

This document summarises the portfolio of submissions that has been presented for the degree of Doctor of Engineering. The portfolio contains fifteen submissions that describe the author's research work plus auxiliary documents. This report explains how the elements of the portfolio fit together and highlights the key achievements and conclusions.

First, the contents of the portfolio will be listed and the framework of the portfolio will be outlined. It will be explained that every submission relates to the general research theme of modelling and analysis of current and concept vehicles for the purpose of enhancing vehicle handling. The order in which it is recommended that the submissions be read will be stated. Then, each submission will be summarised. This will include the motivation behind the reported work, the method(s) employed and the key findings.

Eleven of the fifteen submissions are concerned with the development of a model of drivers' steering behaviour for handling analysis. An overview of this project in its entirety (rather than as it appears in discrete submissions) will be given in section 4. The need for a driver model to simulate the steering of a range of drivers will be explained. The formulation of a driver model that meets this requirement will be presented. It will be demonstrated that the driver model can be used to represent the steering inputs made by different human drivers.

Finally, the application of innovation to the engineering business environment within this research, as required by the Engineering Doctorate programme, will be affirmed.

2 Portfolio Structure

The portfolio contains this, the Executive Summary, fifteen submissions, a Personal Profile, thirteen Post Module Assignments and an Appendix (one paper and two abstracts of papers that have been offered for publication and/or conferences). The submissions describe the research that the author conducted whilst on the Engineering Doctorate programme. The Personal Profile describes the development of the author's competencies over the programme. The thirteen, week-long Engineering Business Management modules that the author attended at the University of Warwick helped in this development. After each module, a forty-hour Post Module Assignment was completed; these are included in the portfolio.

2.1 Theme of the Research

The research presented in the portfolio is concerned with the modelling and analysis of current and concept vehicles for the purpose of enhancing vehicle handling.

2.2 Contribution of Each Submission to the Theme

1. An Analysis of Steering Veer – the analysis of a handling problem; solutions are generated.
2. Vehicle Handling Requirements – the analysis of future requirements of vehicle technology and an investigation into how drivers assess handling.
3. Human Factors Database – web pages to store and disseminate information on human factors that can be used when modelling or analysing handling.
4. Potential versus Risk – a method of evaluating new technology concepts is developed and applied to the Mechanically Interlinked Suspension concept.
5. Driver Modelling – the requirements for a driver model are specified.
6. Mechanically Interlinked Suspension – the concept is introduced and there is an explanation of how it will potentially enhance handling, on-road and off-road.
7. Optimisation of Mechanically Interlinked Suspension: Methodology – the use of Taguchi Design of Experiments and ADAMs to analyse the effect of this concept on vehicle handling.
8. Quantification of Different Steering Styles – drivers' different styles of steering are identified and their effect on handling is analysed.

9. Quantification of Different Steering Styles Part II: Comparison of a Car and a Land Rover – steering styles in different vehicles are examined.
10. Human Performance Modeling: Representation of Different Steering Styles (SAE paper) – a model is developed for the purpose of simulating different steering styles so that realistic handling test conditions maybe recreated.
11. Optimal Control Driver Model - further detail of the driver model introduced in Submission 10.
12. Neural Network Driver Model – a neural network is employed in an attempt to extend the function of the driver model.
13. Linear Optimal Control Driver Model - the solve time of the driver model is reduced by using a linear technique.
14. Application of the Driver Model to the Assessment of Vehicle Handling – this demonstrates the way in which the driver model adds value to concept analysis.
15. Further Work: Project Descriptions – potential areas of further, related research are identified.

2.3 Recommended Order of Reading

The following order of reading the articles in the portfolio is recommended; submissions on the same subject are grouped together.

Analysis and Simulation of Drivers' Steering Behaviour

- Submission 2. Vehicle Handling Requirements
- Submission 3. Human Factors Database – please note that this submission presents a web site so you will need to use a PC with a floppy disc drive and an internet browser such as Microsoft Explorer to fully appreciate this submission.
- Submission 5. Driver Modelling
- Submission 8. Quantification of Different Steering Styles
- Submission 9. Quantification of Steering Styles: Part II
- Submission 10. Human Performance Modeling: Representation of Different Steering Styles (SAE paper)
- Submission 11. Optimal Control Driver Model

- Submission 12. Neural Network Driver Model
- Submission 13. Linear Optimal Control Driver Model
- Submission 14. Application of the Driver Model to Assessment of Vehicle Handling
- Submission 15. Further Work: Project Descriptions

Mechanically Interlinked Suspension

- Submission 6. Mechanically Interlinked Suspension
- Submission 7. Optimisation of Mechanically Interlinked Suspension: Methodology

Other Submissions

- Submission 4. Potential versus Risk
- Submission 1. An Analysis of Steering Veer

Auxiliary Documents

- Personal Profile
- Thirteen Post Module Assignments
- Appendix to the Portfolio. This includes one published paper (Whittaker, L.M.T., Spillane, A.F. and Jones, R.P., "Human Performance Modeling: Representation of Different Steering Styles", *SAE Digital Human Modeling Conference,* Virginia, USA 26th-28th June 2001) and three abstracts of papers submitted for publication and/or conferences.

3 Summary of Each of the Submissions

3.1 An Analysis of Steering Veer

This submission was written following work performed in response to a pressing problem that was generating a large number of warranty claims. The problem of steering veer is apparent when a driver takes his or her hands off the steering wheel and the vehicle drifts away from its straight path. Another effect of the steering veer problem is that the driver has to apply a torque to the steering wheel even when driving in a straight line. Previous investigations into the problem had revealed that there are many potential causes. Hence, the author was tasked with determining the major causes of veer on the particular problematic vehicle with a view to finding a solution.

A mathematical model of the vehicle, which included the aspects that could cause veer, was created. A total of forty-seven vehicle parameters could be varied in the model, including such details as the camber angle of each wheel and anti-roll bar pre-load. The model was used to predict the measure of veer that would be caused by each one of over four thousand different combinations of values of the parameters. This number of predictions is impractical to perform using the industry's favoured vehicle dynamics modelling software - ADAMs; the faster, bespoke veer model made it possible.

The submission reports that there are three major causes of veer in the vehicle in question. They are anti-roll bar pre-load, tyre conicity (the slight cone-shape of some tyres) and mass distribution across the front axle. Recommendations from this work resulted in an in-service fix being developed whereby an elongated suspension link is used to alleviate anti-roll bar pre-load and over £35,000 was invested in implementing a design change that reduces the potential for the anti-roll bar to cause veer. Since this submission was written, the author has advised on steering veer when it has occurred on other vehicles, the model has been supplied to other Ford Motor Company firms and the author has used a modified version of the model to investigate steering feel on another vehicle programme.

3.2 Vehicle Handling Requirements

Submission 2 is in three parts. The first section was written to give guidance to the company's Chassis Concepts department (which had been formed barely a year earlier) as to what the future requirements of vehicle chassis are likely to be. A wide range of documents and papers predicting future trends were collated and their relevance to chassis was discerned. It was determined that one of the key influences on chassis requirements would be the growth of niche vehicle markets. This will require product differentiators including enhanced and customised vehicle handling, afforded by predicted advances in electronic chassis control systems.

The remainder of Submission 2 focuses on the need to understand how drivers judge vehicle handling in order to provide enhanced and/or customised handling. Hence, part two is a literature review of the factors that influence drivers' opinions of the entire driving experience, as it was found that drivers generally find it difficult to assess handling characteristics independently of their overall impression of driving a vehicle. It was ascertained that a significant influence on the driver's evaluation of vehicle handling results from factors that are a product of the driver/vehicle combination. That is, the performance of the driver/vehicle combination as well as the characteristics of the vehicle alone, influence the driver's evaluation of the vehicle's handing.

The third and final part of Submission 2 concludes that it should be possible to model many of the factors that influence the driver's evaluation of vehicle handling. Such a model would enable vehicle manufacturers to evaluate how a new vehicle might be received by its target customers. Hence, it was proposed that a model be developed to simulate a range of drivers for use in handling analyses.

3.3 Human Factors Database

Submission 3 presents a computer disc containing a web site created for storing and disseminating data on human factors in driving. The author discovered that there is little data within the company on the characteristics of drivers and wished to share the information collected during the study reported in Submission 2. Much of the literature searched for Submission 2 was irrelevant or inconclusive, in contrast, the web site includes only that information that is directly relevant to vehicle development. It was intended that the web site be included in the company's intranet[1] with a note to

[1] The intranet is similar to the internet but it can be accessed only from authorised computers that are under the company's control.

encourage others to contribute to it. However, due to the division of the company, it has not yet been possible to put it on the intranet for reasons of confidentiality.

3.4 Potential versus Risk

This submission documents a process devised to help Chassis Concepts select the most appropriate concepts for development. The department has limited resource and it is vital that its portfolio of projects utilises its resources effectively. The process assists in identifying and quantifying the potential performance of the concept and the risks and cost involved in developing it. The process was developed following a study of research practices in other industries and literature on successful innovation in business.

The process has four stages. The Innovation Table lists many aspects of chassis and suspension and asks whether they will evolve from existing parts or will require innovation. The Risk Matrix is used to quantify the risk involved in developing the identified innovative aspects. The Action List provides prompts for establishing what resource will be needed to address the risks to the project. Finally, the risk of failure of a project, the potential performance of the concept and the estimated cost of the project are compared. The submission reports upon a particular application of the process. Two designs of a new concept called Mechanically Interlinked suspension had been formulated and the process was used to choose between them.

3.5 Driver Modelling

This submission follows on from Submission 2, which concluded that a driver model was required for the purpose of investigating vehicle handling enhancements. Some driver models documented in the literature and a commercially available driver model, IPG Driver[1], were assessed but, as Submission 5 reports, none are ideal for the proposed use. Hence, the

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[1] IPG Driver from IPG Automotive Software and Consulting GmbH.

work detailed in Submission 5 was motivated by the need to develop a bespoke driver model.

To begin, Submission 5 elaborates upon the objectives for the driver model, with particular reference to its role in the development of off-road vehicles. A structure for the model that will satisfy the objectives is formulated. The structure contains four key elements; human elements, including sensitivity to motion and reaction time; learning, i.e. a way in which the driver can adapt to different vehicles; the input(s) that the driver model receives; a goal, i.e. the driver's motivation. Then, consideration is given to various methods of modelling drivers that are reported in the literature. It is proposed that a cost function be used to embody the driver's goal and a neural network technique called model reference control be employed.

3.6 Mechanically Interlinked Suspension

Submission 6 presents a four page, colour brochure that the author produced to promote one of the department's patented new concepts [1]. The brochure was required to explain the function and performance of Mechanically Interlinked Suspension to senior level personnel in departments including Finance and Marketing. It has generated enthusiasm for the concept.

3.7 Optimisation of Mechanically Interlinked Suspension: Methodology

This submission describes a rigorous approach to the optimisation of Mechanically Interlinked Suspension at the concept stage; that is, when only models of the vehicle are available. This new concept suspension system was first introduced in Submission 6.

The traditional approach to the optimisation of suspension design using historical knowledge of the system was not applicable because of the novelty of Mechanically Interlinked Suspension. In addition, each iteration of changing a design parameter, running the simulation and recording the results takes over forty minutes so it is time-expensive to examine many configurations of the design. Instead, a Taguchi array of experiments was used to investigate the effect of four key design parameters on the suspension's performance.

For the experimental work, a model of the concept in ADAMs, the multi-body systems simulation software package, was utilised. In the submission, the author defines a method for measuring a particular aspect of off-road performance, cross axle articulation, using an ADAMs model. Then, the on-road and off-road performance results for each design configuration in the Taguchi array are presented.

The submission identifies which design parameters have the greatest influence on the concept's performance. It is concluded that the use of the Taguchi array of experiments provided valuable design guidelines and enabled a range of designs to be evaluated quickly and methodically. It is advocated that this approach be used during the development of other concepts in the future.

3.8 Quantification of Different Steering Styles

In Submission 5, a structure for a driver modelling for the assessment of vehicle handling was proposed. Submissions 2 and 5 both recognised that different drivers drive differently hence one objective of the driver model is that it represents a range of different drivers. The tests reported in this submission were undertaken in order to gain understanding into the differences between drivers and aid the development of the driver model.

Six drivers of different ages, gender and driving experience, were asked to drive a mid-size saloon car through a single lane change course, marked out with cones. Instrumentation on the car measured and recorded data including steering wheel motion, lateral acceleration, yaw rate and roll angle. Each driver drove through the course ten times at two speeds, 25mph then 35mph. The first five runs gave the driver a chance to familiarise himself/herself with the car; only the final five runs were analysed.

An analysis of the test results showed that each driver exhibited their own unique style of steering that was repeated on each run. The difference in peak steering wheel angle between two of the drivers was found to be 100% in magnitude. It was shown that the differences in steering style resulted in different drivers experiencing peak levels of vehicle motion that also differed by 100% between drivers. It was concluded that, because a driver's steering style affects his/her experience in the vehicle, steering style influences a driver's evaluation of the vehicle. This reinforced the need for a driver model that can simulate different drivers.

A paper based on this submission entitled "Quantification of Steering Styles" is reproduced in the portfolio's appendix and, in September 2000, was sent to the International Journal of Vehicle Design. However, the editor has not yet responded.

3.9 Quantification of Steering Styles Part II: Comparison of a Car and a Land Rover

Submission 9 reports upon tests performed in a Land Rover that has an active chassis control system (Active Cornering Enhancement, which regulates roll). The results are compared to those from Submission 8. The work was performed to further understand the different steering styles exhibited by drivers in order to enable the development of a driver model that mimics this behaviour. In particular, the tests in the Land Rover were undertaken to determine whether or not these large vehicles cause greater differences between drivers than a car. Furthermore, the tests were conducted both with the chassis control system activated and with it disabled to ascertain the extent to which drivers adapt their steering inputs in response to the control system.

The primary findings of Submission 9 are that the difference between drivers' steering styles is no greater in the Land Rover than in the car and that drivers do not adapt their steering style in response to the active chassis control system. In fact, the results showed that the steering of an individual driver changes only in magnitude between the two vehicles, enough to take account of the difference in steering ratios. Similarly, steering input changed with speed in a way that meant each individual driver steered with approximately the same angle at each point along the length of the course, regardless of speed.

3.10 Human Performance Modeling: Representation of Different Steering Styles

A paper entitled "Human Performance Modeling: Representation of Different Steering Styles" by Whittaker, Spillane and Jones is presented in this submission. This paper was presented, by the author of this portfolio, at the SAE Conference and Exposition on Digital Human Modeling for Design and Engineering in Arlington, Virginia, USA 26th-28th June 2001. Funding for the trip was provided by the Institution of Mechanical Engineers, the Royal Academy of Engineering and the Engineering and Physical Sciences Research Council. A review of the conference, which has been sent to these benefactors, is included in the submission.

The subject of the paper is the development of a driver model that is discussed in greater detail in Submission 11. The test results from Submission 8 are used to demonstrate the existence of two different steering styles. Then, optimal control theory is used to formulate a driver model that can simulate both steering styles. The driver model is shown to successfully negotiate a single lane change.

3.11 Optimal Control Driver Model

In this submission, the optimal control driver model introduced in Submission 10 is described in greater detail. In addition, included are results from the driver model controlling a model of a Land Rover as well as a saloon car.

Optimal control theory is used to embody the driver's goal in a cost function, as proposed in Submission 5. The optimal control driver model is designed to negotiate the same course used in the tests described in Submissions 8 and 9 thus validation is possible.

A review of the literature reveals that current approaches to driver modelling require the driver to track a predefined path. Furthermore, it is reported that recent work on the modelling of ideal lane change paths does not include the influence of driver behaviour or the vehicle dynamics on the paths taken by a vehicle during the manoeuvre. Conversely, with the optimal control driver model, the vehicle path is determined by driver motivation, which is encapsulated in the driver model. It is shown in this submission that the optimal control driver model is capable of representing the diverse steering styles of two real drivers in both a saloon car and a Land Rover. This is achieved by adjusting the parameters in the cost function. The parameters in the cost functional are then discussed in relation to specific aspects of a driver's character, including cautiousness, for example. The disadvantage of the method employed is in the iterative solution; it takes two hours to calculate the optimal control for each set of parameters when using MATLAB[1].

The optimal control driver model is used to investigate the path taken through the course in different vehicles. Following this, Submission 10 introduces the hypothesis that each driver has their own unique pattern of steering which is simply scaled to enable them to negotiate the lane change in different vehicles and at different speeds. This theory is then likened to research showing that humans repeat patterns of movement when walking or writing that have the same proportions in time and space, regardless of the size or speed of the movement.

3.12 Neural Network Driver Model

The optimal control driver model was found to be very successful but time consuming to solve. Hence, the use of the optimal control driver model to train a neural network is explored. This work was motivated, in part, by the anticipation that a neural network driver model could be used to negotiate more complex manoeuvres than a single lane change without resulting in an impractical solve time. Additionally, it was expected that the neural network

[1] MATLAB®, from The MathWorks Inc, is a software package that integrates mathematical computing, visualisation and a technical programming language.

driver model would be easier to use and thereby would encourage its application by colleagues.

The submission first introduces neural networks. Then, the various options available in neural network design are discussed and selected. Consideration is given to the detail of the training data used. In particular, the inputs to the driver model are deliberated, including that which provides preview information on the road ahead.

Two neural network driver models were created; one that represents a driver in a particular car and one that represents the same driver in a Land Rover. The performance of the neural network driver model is found to be exemplary when considered as a stand-alone object; it is very capable of predicting the required steering wheel angle given a particular set of conditions. However, it is recognised that the path described by the vehicle model when controlled by the neural network driver model is the more pertinent aspect of performance. In this situation, the output of the neural network is used to control a vehicle model. The motion of the vehicle model is then used as an input to the neural network. It was found that this resulted in a build-up of errors that could cause the vehicle to fail the lane change, hence, the specifics of training the neural network proved critical. Further difficulties arose in generating a driver model that could represent more than one driver or drive more than one vehicle. The lengthy process of finding the combination of factors that resulted in a satisfactory neural network driver model and the limited capability of the resulting neural network driver models resulted in the decision to discontinue this approach.

A proposal, in the form of an abstract, for a paper to be based upon this work has been submitted to the Mathworks Conference on Automotive Modelling and Simulation, Staverton, Northamptonshire, October 2001. The paper is entitled "Utilisation of the MATLAB Neural Network Toolbox for Modelling Drivers' Steering Styles". The co-author of the paper is R.P. Jones. The abstract is included in the portfolio appendix.

3.13 Linear Optimal Control Driver Model

In an alternative effort to reduce the solve time of the optimal control driver model introduced in Submissions 10 and 11, the solution of the linear-quadratic tracking optimal control problem is employed. This necessitates a linear vehicle model. The solution of this problem is quicker than the iterative method used previously.

Like the iteratively solved optimal control driver model, the linear optimal control driver model is shown to successfully negotiate the single lane change and represent different steering styles. The linear optimal control driver model takes just thirty seconds to solve using MATLAB, thus, is more practical to use than the iterative solution.

The driver model is formulated in the format of the standard linear-quadratic tracking optimal control problem. The solution of the problem is presented and is also illustrated graphically. It is demonstrated that certain aspects of the solution of the linear-quadratic tracking optimal control problem relate to how real drivers operate. It is explained that the solution of the problem includes both feedforward and feedback elements. The feedforward signal is dominated by heading angle and position information, rather than vehicle motion information. Moreover, the feedback gain is independent of the required manoeuvre; it is influenced instead by the vehicle dynamics and the driver's goal.

An abstract for a paper entitled "A Linear Quadratic Optimal Control Approach to the Simulation of Driver's Steering Styles" has been submitted to the IMA (Institute of Mathematics and its Applications) Conference on Advanced Simulation and Control for Automotive Applications, Oxford, September 2001. R.P. Jones is the co-author of this paper. The abstract is included in the portfolio appendix.

3.14 Application of the Driver Model to the Assessment of Vehicle Handling

Knowledge gained about drivers' steering behaviour and the linear optimal control driver model are used to investigate variable dampers. The benefit of variable dampers to ride comfort has already been established [2] and, now, manufacturers of rheologically variable dampers claim that they can be used to enhance handling [3]. This submission describes an investigation into the potential of variable dampers to influence handling to an extent that a driver would appreciate whilst on a typical journey. This study also provides an opportunity to evaluate the usefulness of the driver model.

Simulations of a single lane change using the driver model are used to develop a switching strategy that increases the vehicle's responsiveness when turning into a cornering manoeuvre. The steering inputs of different drivers are used to verify that the variable dampers have the potential to reduce the roll angle and roll rate experienced by drivers with different steering styles. The change in steering input that a driver must make between a standard vehicle and a vehicle with variable dampers in order to negotiate the same lane change is determined. The effect of variable dampers on handling is compared to the effect of putting a stiffer anti-roll bar on the rear, which is known to change handling characteristics.

The modelling and simulation establishes that variable dampers have the potential to enhance handling during regular driving tasks. The next step is to validate this against a prototype vehicle fitted with sets of passive dampers of different rates. It is demonstrated that the simulations with the driver model provide additional, useful information beyond that of the traditional analysis of vehicle response to standard inputs. In particular, it allows different vehicle configurations to be assessed under comparable conditions. That is, over the same course rather than in response to a given steering input, which might result in different configurations of the vehicle taking very different paths. Moreover, the driver model provides the opportunity to ensure that different drivers will benefit from variable damping before a prototype is available for different drivers to assess.

3.15 Further Work: Project Descriptions

The author's investigation into drivers' steering behaviour identified several areas where further work would be of value. Moreover, some data and results amassed during the author's project have not yet been fully explored.

Hence, six self-contained work packages are presented in this submission. Some of the tasks build upon existing data and/or results and other tasks suggest using the driver model to examine specific vehicle handling issues.

4 Analysis and Simulation of Drivers' Steering Behaviour for Vehicle Handling Assessments: A Project Summary

4.1 Introduction

The research described here was undertaken in the author's capacity as an employee of Land Rover[1], an automotive manufacturer. The company develops vehicles that are sold at a premium price and its mission is to strengthen this market position. The company's strategy for achieving this includes a requirement to deliver vehicle handling that delights the customer. The chassis and suspension technology that will be capable of fulfilling the needs of the customer in five or ten years time needs to be in development now. Therefore, work is currently being undertaken by the company to develop vehicle concepts that will deliver enhanced handling on future products. The research summarised in this document contributes to this aspect of the business plan.

Predictions of the nature of the vehicle market from a variety of sources have been used to understand the demands on vehicle handling in the future (this is discussed in more detail in Submission 2). It is expected that the vehicle market, like many markets [4], will become more segmented with high profits to be made on niche (or "lifestyle") vehicles. Demographics will influence this as the customer base broadens beyond the traditional purchaser, who is male and aged between 30 to 50 years. Firstly, more potential customers will be elderly because the over 65 population is increasing rapidly [5]. In addition, the volume of vehicles sold to women is increasing as more are now in employment [5]. Indeed, in the USA, in 2000, 50% of vehicle purchases and leases were made by women [6]. Furthermore, the growing proportion of young adults living with their parents

[1] It should be noted that, at the time when this research commenced, the company also manufactured Rover cars.

[5] is contributing to the disposable income of this sector. The current trends of increasing disposable income and more households with second and third cars will also fuel the market for vehicles that reflect and complement the individual purchaser's lifestyle. This market of niche products will be facilitated by advancements made by manufacturers in developing cost-effective, low volume production facilities [7]. These products will require vehicle handling characteristics that have been designed to suit their niche and indeed, their particular customers. For example, a vehicle targeted at the elderly population would benefit from handling characteristics that are sympathetic to the 14% longer reflex time of the average 68 year old over a 21 year old [8].

Looking further in to the future, the mass customisation of vehicles may warrant the customisation of vehicle handling. Already, the Smart Car, a mass produced product, can be customised by selecting from a range of interchangeable colour panels [9]. Similarly, PCs are made to order by Dell and Gateway [9]. As people become accustomed to customised products in some areas of their lives, they will begin to expect them in other areas, such as vehicle handling.

The transformation of a vehicle's handling to suit future customer requirements will be facilitated by active chassis control systems, as the literature confirms. Indeed, this is part of the well-established, more general trend of the increasing electronic content of vehicles. This is supported by government-funded projects such as Intelligent Transport Systems [10] and advances in computing, actuators and sensors. Existing systems for vehicle handling control include Direct Yaw-moment Control (DYC) [11, 12], four-wheel steering [13] and active torque split control between wheels [14, 15]. The most common active chassis control systems on current production vehicles are those aimed primarily at improving safety. For example, DYC uses a braking torque at one or more wheels to counteract excessive yawing of the vehicle. To meet the demands of the future, handling in the normal driving regime will need to be enhanced so that the customer appreciates it during his or her first test drive and every drive thereafter.

The need for enhanced vehicle handling in the future is clear and it appears that this can be achieved through the judicious use of active chassis control systems. In order to develop such systems efficiently, an understanding of how drivers evaluate vehicles and the capability to explore this prior to prototyping are required. In this project summary, the first section will present the human factors that affect drivers' evaluations of vehicles. The importance of the driver and vehicle combination rather than the vehicle alone will be explained. Then, the sections that follow will summarise an investigation into the interaction between driver and vehicle through the steering wheel and the development of a driver model. The understanding of drivers' steering behaviour gained from two sets of vehicle tests (reported in full in Submissions 8 and 9) will be outlined. It will be demonstrated that each driver uses a different steering input to negotiate the set course and, therefore, each takes a different path. The scale of the differences between the steering inputs of different drivers over the same course will also be revealed. It will be shown that different drivers experience different vehicle motion during the same manoeuvre. Then, existing driver models will be reviewed against the criterion of simulating different drivers, each of whom may take a different path through a course. It will be explained that no existing driver model fully meets the company's requirements. However, certain aspects of existing driver models will be selected for utilisation in the new driver model. In section 4.4.3, the formulation of a driver model that can simulate these differences between drivers will be described. Optimal control theory is used to formulate the driver model; a cost functional represents the driver's motivation. It will be demonstrated that assigning different relative weights to driver effort, vehicle motion and path results in the driver model using different steering inputs to negotiate a course. Finally, the application of the driver model and the new-found understanding of drivers to a particular investigation of vehicle handling will be reported. The driver model will be used to assess the potential of variable dampers to enhance vehicle handling to the extent that an ordinary driver is likely to appreciate it. The analysis using the driver model will be compared to a traditional, step-steer response analysis to identify the additional information provided by the driver model.

4.2 Human Factors in Driving

A literature review regarding the factors that influence drivers' evaluations of vehicles is presented in Submission 2. Included are the findings from the many experiments that have been performed to study the effect of different vehicle parameters on the driver's subjective impression of a vehicle [16], the driver's ability [17] and the driver's stress levels [18]. Figure 1 illustrates the salient findings of Submission 2. It shows all of the factors that affect a driver's impression of driving a particular vehicle. The figure shows that only a small number of factors are attributed to the vehicle alone. Instead, a significant influence on the driver's evaluation results from factors that are a product of the driver/vehicle combination. That is, some of the driver's own attributes and actions affect the way in which he or she feels about the vehicle. Thus, it is of vital importance to consider the driver/vehicle combination rather than the vehicle alone when analysing vehicle handling.

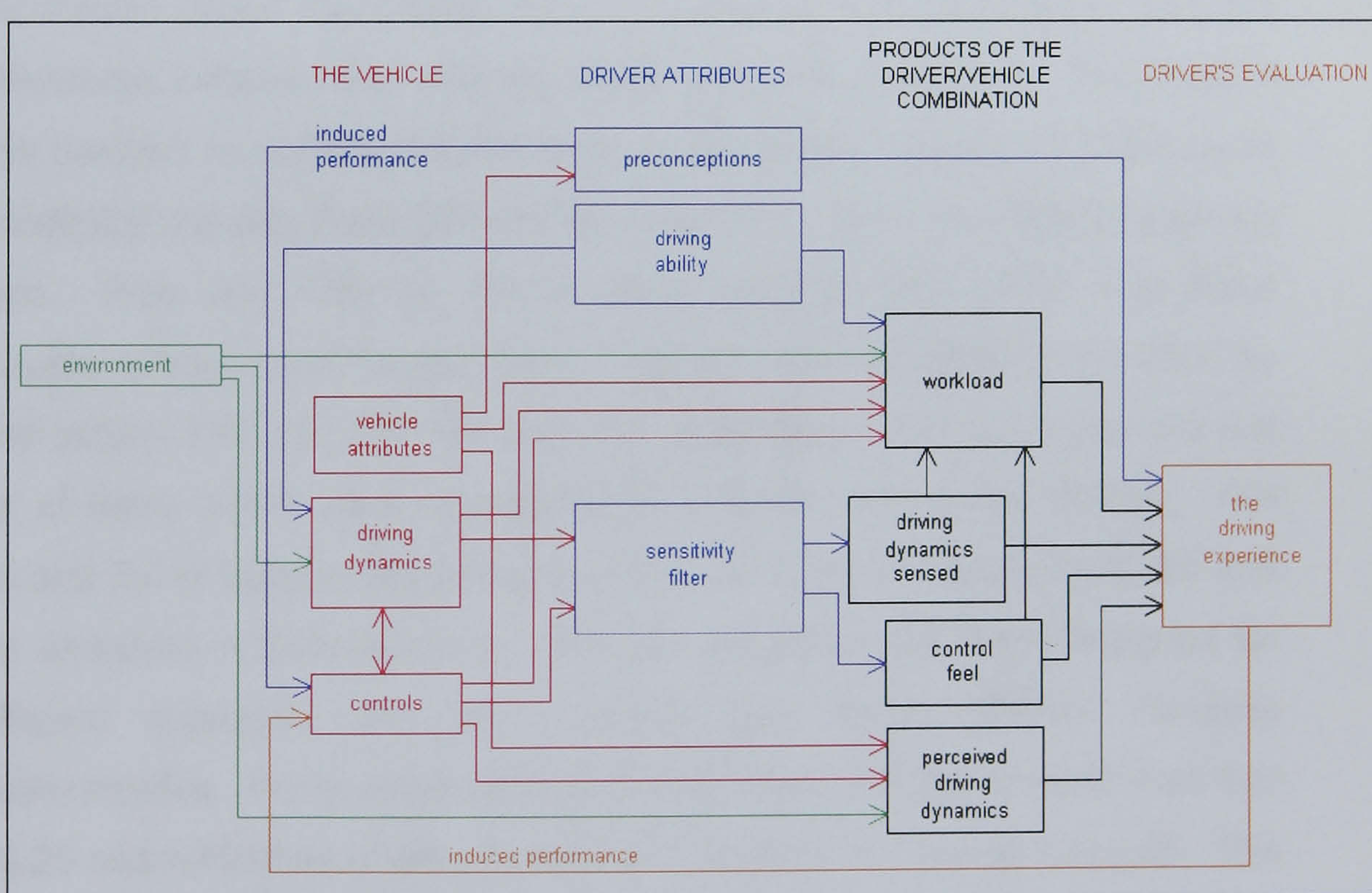

Figure 1. Diagram of Human Factors in the Driving Experience

Prior to the work reported here, much of the development of active chassis control systems was performed using vehicle models but without a model of the driver. Moreover, there was little understanding of drivers' steering behaviour; what influences it or how it differs between drivers. Thus, it was determined that drivers' steering behaviour be investigated and that a driver model be developed. The proposal was that the driver model be used in conjunction with the company's concept vehicle models and control design tools, for which MATLAB and Simulink[1] are used. The driver model needs to represent a range of drivers in a variety of vehicles. It is to be used to assist in optimising each driver/vehicle combination and to measure any improvements afforded by active chassis control systems.

4.3 Analysis of Drivers' Steering Behaviour

The vehicle tests reported in Submissions 8 and 9 were inspired by Willumeit's [19] assertion that the steering inputs of drivers are like handwriting in that each driver has their own characteristic style. The results of the tests were used to guide the development of the driver model and to validate it. Willumiet studied a number of drivers in one vehicle. Little information about the drivers (age, experience, etc.) was given and the differences between the steering styles was not quantified. Therefore, it was decided to perform vehicle tests in two of the company's products to investigate the effect that differences in handling have on a driver's steering style. Five very different drivers were selected, two males and three females whose ages ranged from 21 to 49. The drivers are identified by their initials; HW, JG, LW, RH and TC. Submission 8 reports upon the first set of tests, which were conducted in a Rover saloon car (R400). The second set of tests were carried out in a Land Rover Discovery (L25) and are analysed in Submission 9. The two vehicles have been designed for different objectives and as a result they have different handling characteristics. For example, the centre of gravity of R400 is lower than that of L25 and R400 has smaller moments of yaw and roll inertia than L25. The

[1] Simulink®, a MATLAB tool, is an interactive tool for modelling, simulating, and analysing dynamic systems. It enables the user to build graphical block diagrams, simulate dynamic systems and evaluate system performance.

tests on L25 were done with its active chassis control system (ACE, which suppresses roll) functioning and then with it disabled. Hence, the effect of active chassis control on steering styles could be assessed.

The test were done on a single lane change course at 25mph and then at 35mph. The course was marked out with cones, as shown in figure 2.

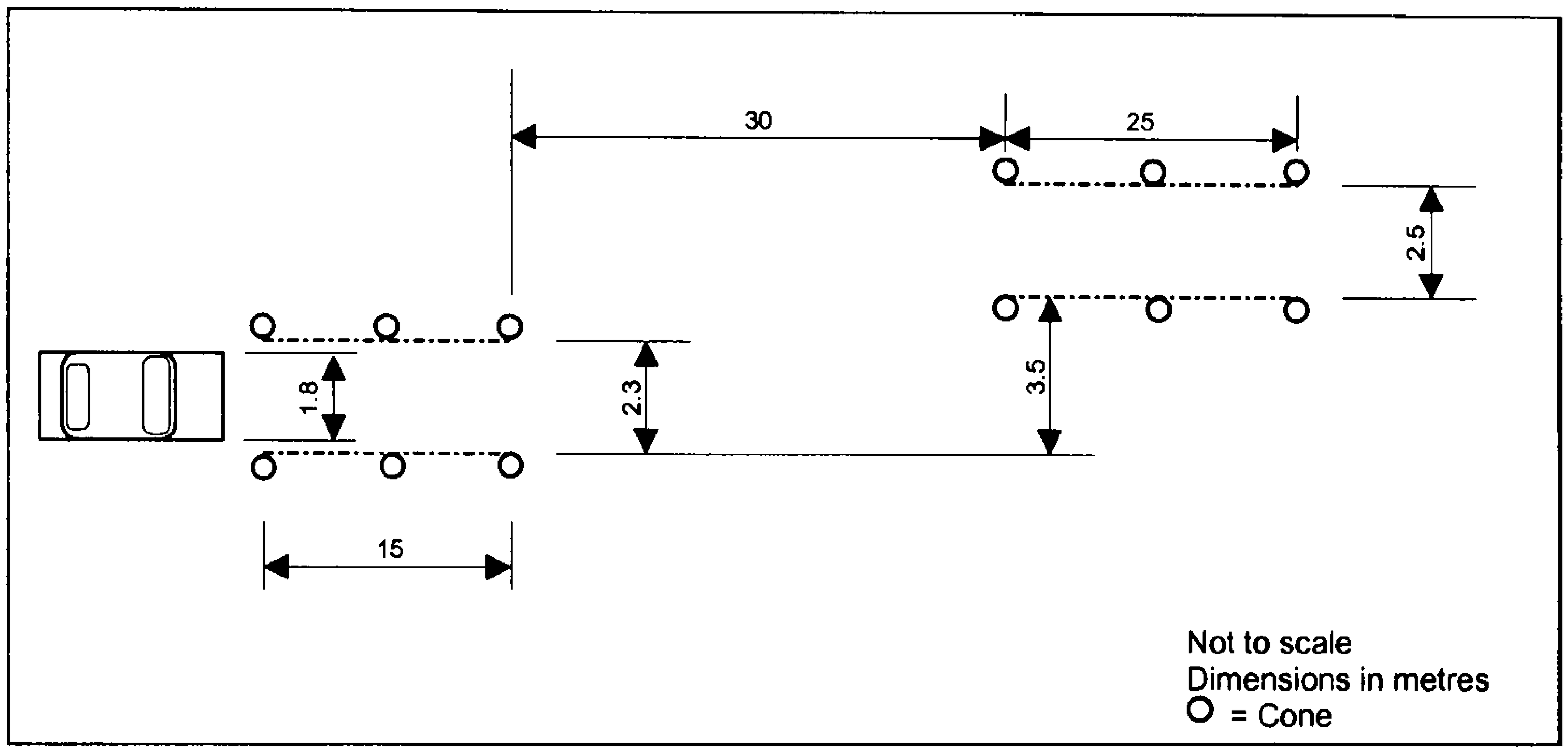

Figure 2. The Course.

L25 is 1.8 meters wide and R400 is 1.6 meters wide so the lanes are quite narrow in comparison. The test speeds were chosen such that the manoeuvre feels like something a driver might do on an average day; it is not an emergency avoidance manoeuvre. At each speed and in each vehicle condition, each driver drove through the course ten times. It was observed that it could take five runs for the driver to become familiar with the manoeuvre and begin using a repeatable steering input. Hence, the only the second set of five runs were used in the analysis. Figure 3 shows one such set of steering inputs from driver JG.

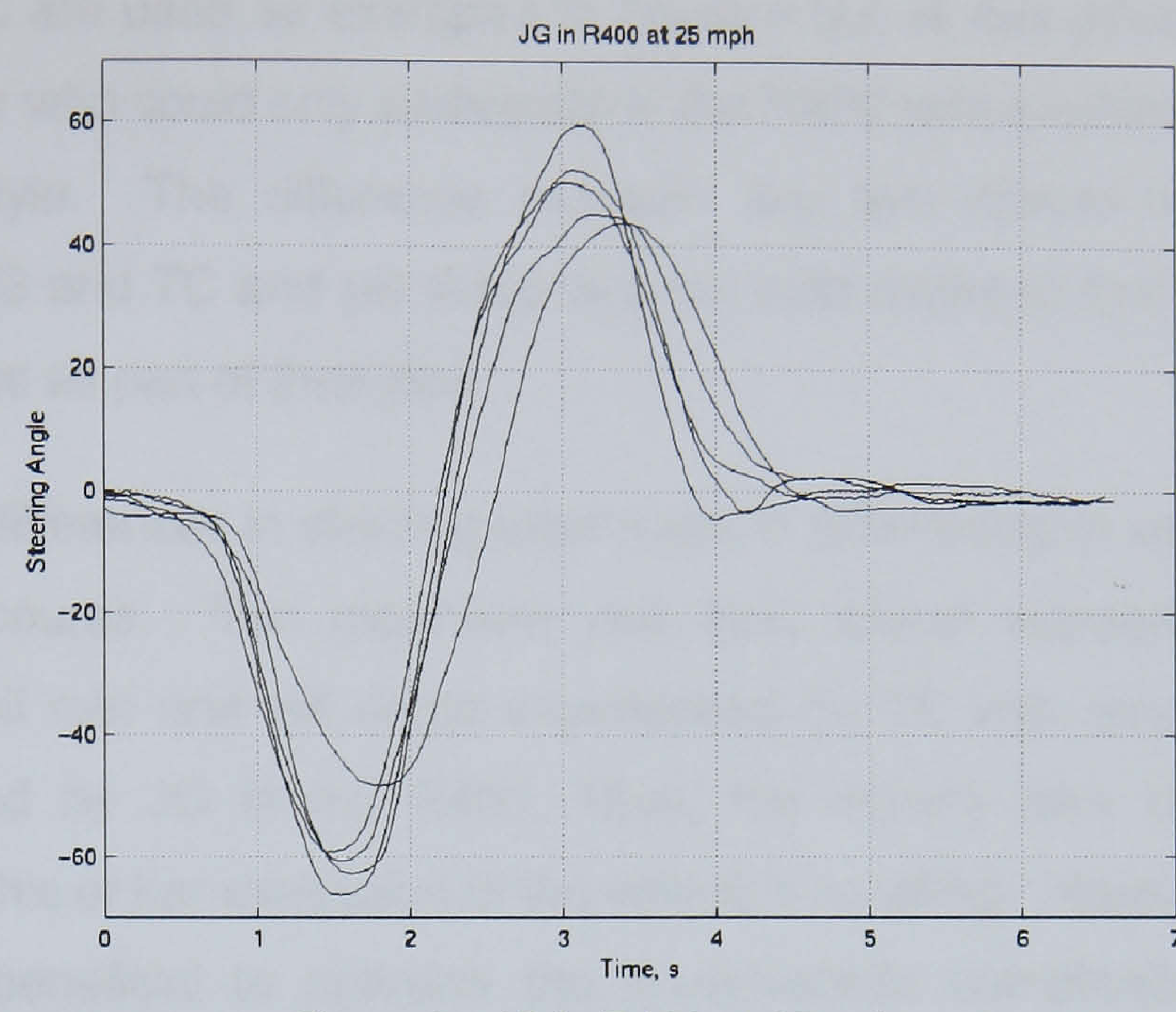

Figure 3. JG in R400 at 25mph.

Figure 3 demonstrates the steering style of one driver. On each run through the lane change, JG repeats the same steering input. The steering style of this driver contrasts with the steering style of another driver, TC, as figure 4 shows. TC, too, exhibits a repeatable steering style. However, TC uses steering angles that are half the magnitude of JG's. The points on the course at which drivers started and finished their manoeuvring also differed between drivers. Driver JG has longer periods than TC of not making any significant steering inputs. However, both drivers successfully negotiated the course.

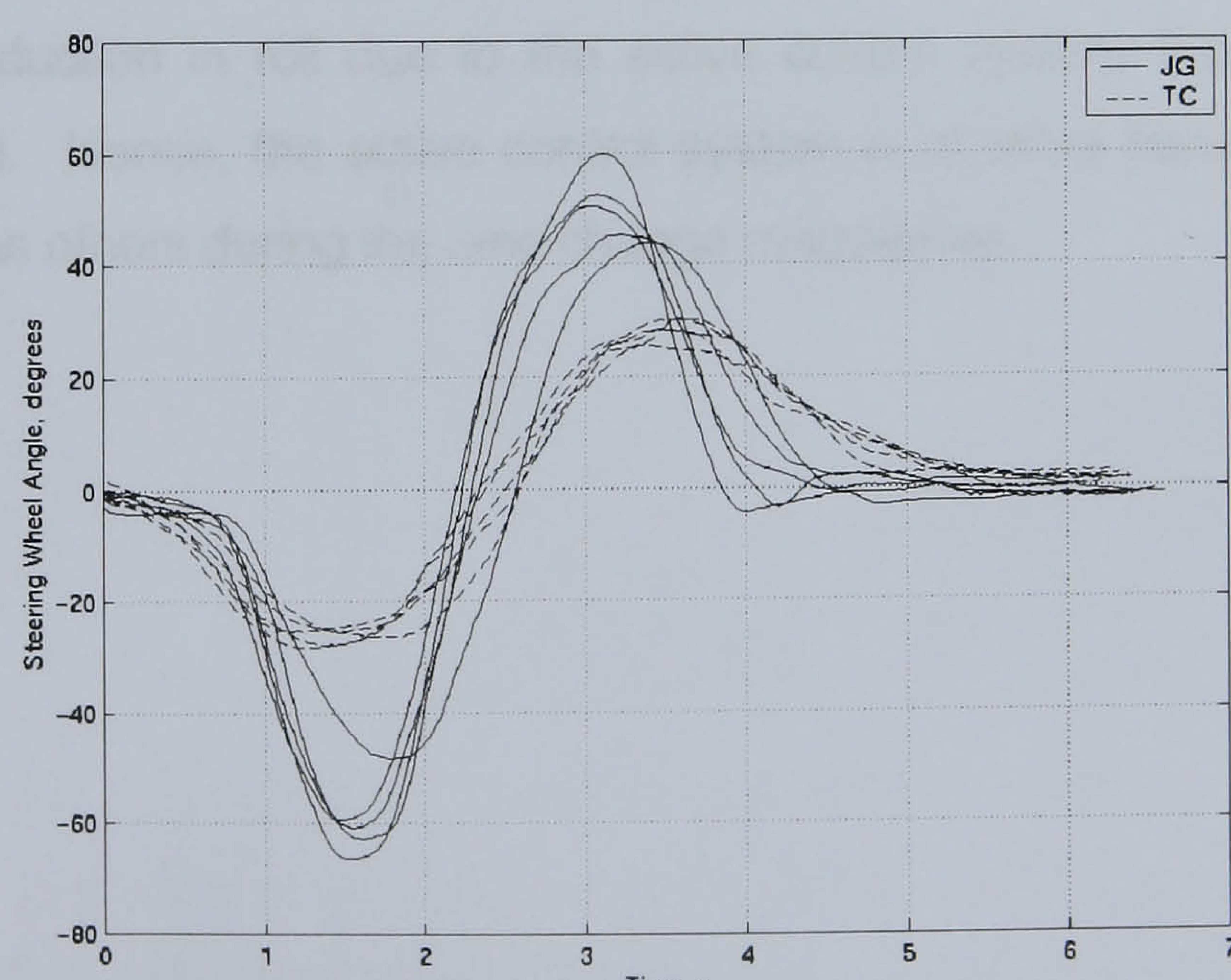

Figure 4. JG and TC in R400 at 25mph.

JG and TC are used as examples in figure 4 but all five drivers (plus one more driver who could only participate in the R400 tests) exhibited a unique steering style. The difference between any two drivers was greatest between JG and TC and yet these two are both males in their thirties who test vehicles as part of their jobs.

Naturally, differences in steering input result in differences in vehicle motion over the course. The maximum yaw rate, lateral acceleration, lateral velocity, roll rate and roll angle experienced by TC was around half that experienced by JG in the R400. Thus, the driver's own steering style influences his or her evaluation of the vehicle's handling. Moreover, it would be more beneficial to optimise the driver/vehicle combination than the vehicle alone.

The tests in L25 revealed that the steering input made by each individual driver did not alter when active control system was disabled. Figure 5 shows that the active control system does significantly reduce the vehicle's roll during the manoeuvre. It can be seen that drivers HW and JG did not adapt their steering style to accommodate this change, this is true of all five drivers. The active control system ensured that each driver experienced similar levels of roll, regardless of their steering style. This is in contrast to the passive vehicle, in which one driver experienced roll double that of another. The drivers making the larger steering inputs experienced a greater reduction in roll due to the active control system than the other drivers did. Hence, the active control system is of more benefit to some drivers than others during the lane change manoeuvre.

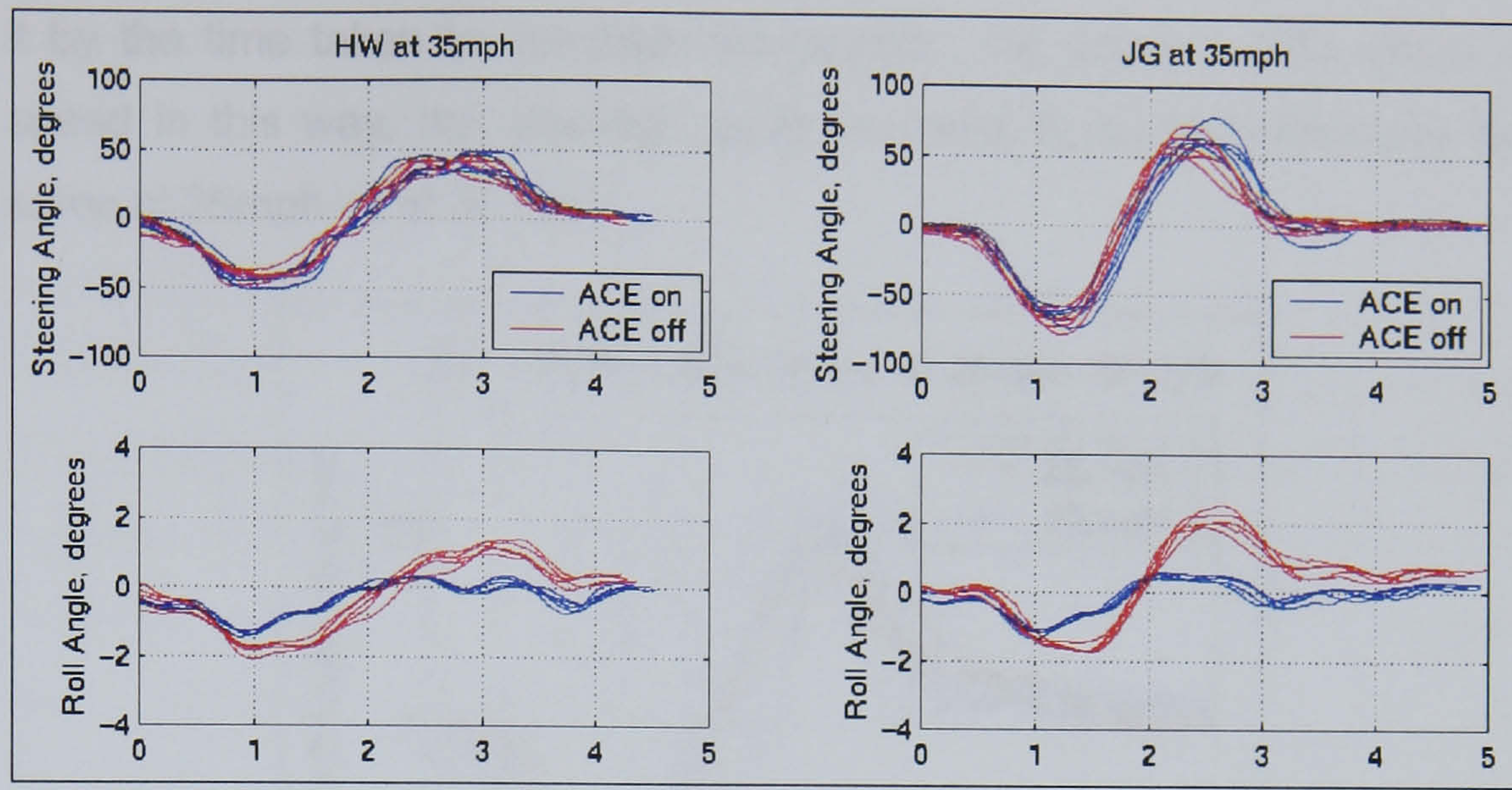

Figure 5. L25 at 35mph.

The tests in R400 and L25 were carried out seven months apart. However, each driver still uses the same steering input to negotiate the course (adjusted only for steering ratio). Figure 6 illustrates this by showing the steered angle generated at the road wheel by JG in R400 and L25 with the active control system on and off. The steered angle is the same in all vehicle conditions. The only exception was driver TC, whose steering input changed in magnitude between R400 and L25.

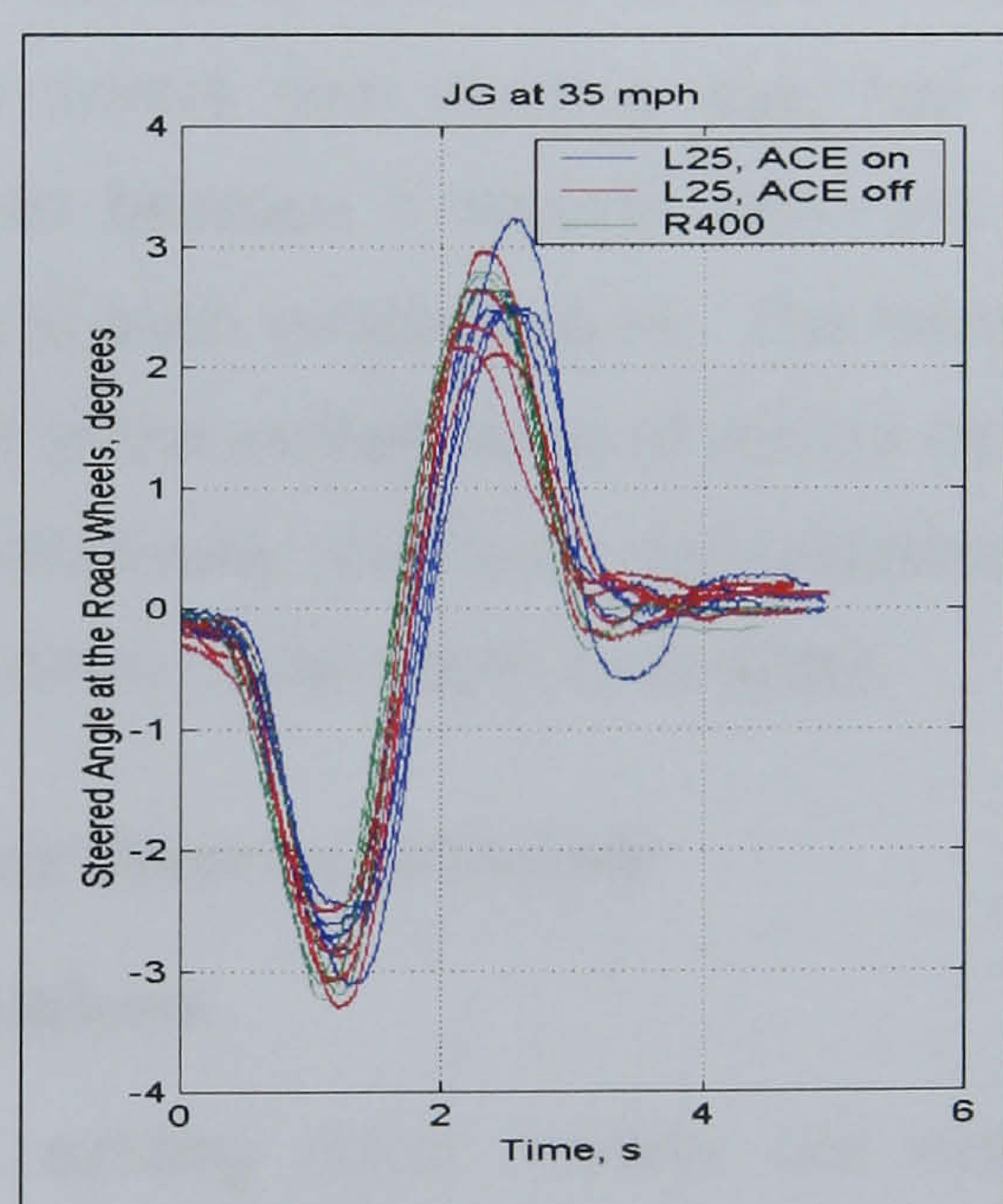

Figure 6. JG at 35mph.

In addition to using essentially the same steering input in different vehicles, it was found that each individual driver simply scaled his or her steering input with respect to time when doing the manoeuvre at different speeds. Figure 7 shows an example of this. The time axis has been normalised by dividing it by the time taken to complete the course. By taking out the effect of speed in this way, the steering inputs are seen to be fundamentally the same at 25mph as at 35mph.

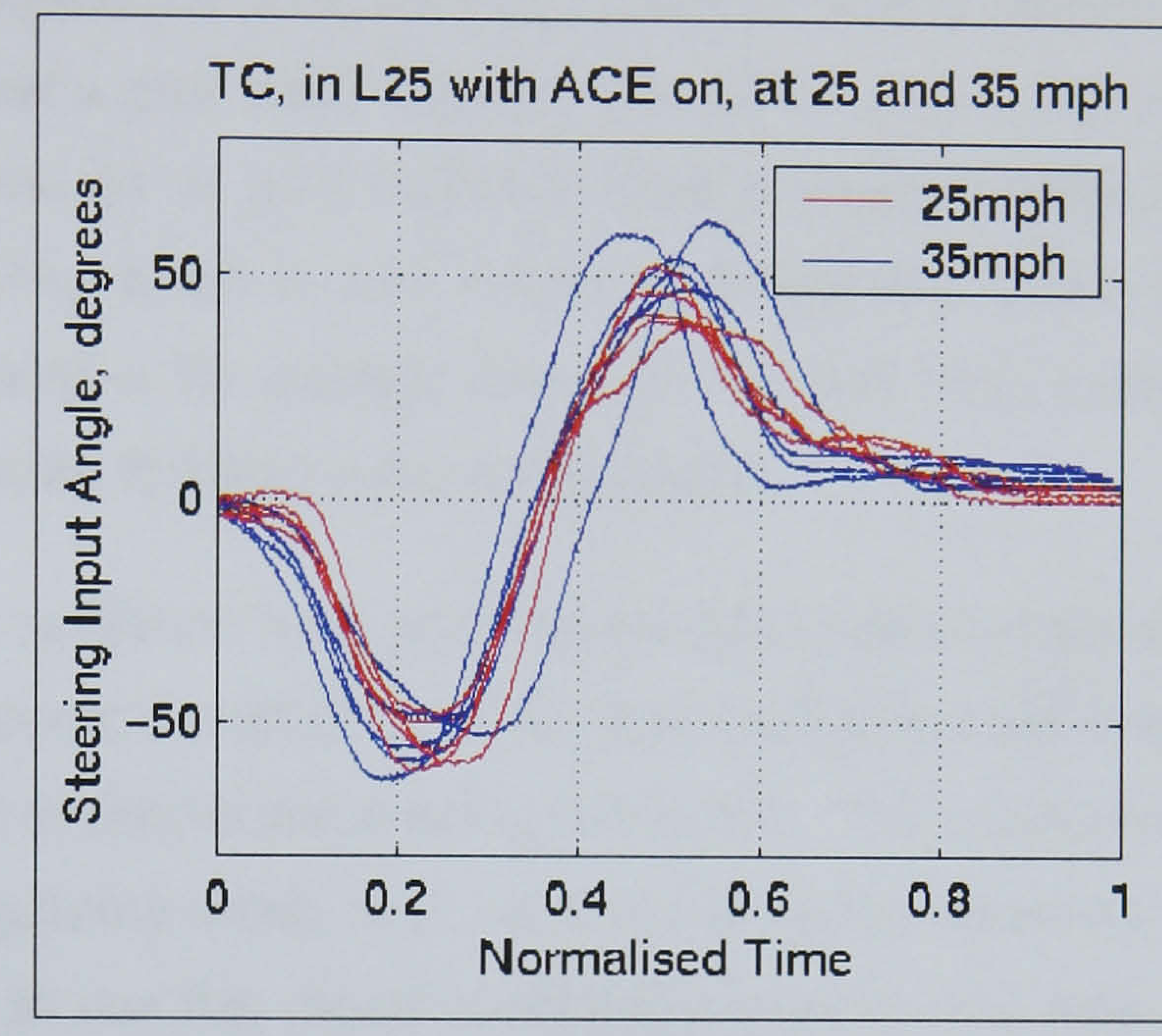

Figure 7. TC in L25.

The scale of the differences between drivers over this course was far greater than was expected by the company's chassis engineers. The realisation that the benefit afforded by an active chassis control system depends upon the driver's own steering style has also been met with surprise and interest because it impacts upon the cost versus benefit consideration given to each vehicle feature. The tests reinforced the need to include the driver at the earliest stage of vehicle development through a driver model. Furthermore, the tests demonstrated the extent of the differences that the driver model needs to simulate.

4.4 Simulation of Drivers' Steering Behaviour

4.4.1 Existing Models of Drivers

In Submission 5, existing driver models are evaluated against the company's requirements of a driver model. The driver model needs to simulate the different steering styles exhibited by different drivers. Furthermore, vehicle tests by Breuer [20], indicate that driving behaviour is influenced by the driver's own goal. These tests were used to investigate the differences in driving behaviour between journalists and non-journalists.

They were performed following unfavourable reports from the motoring press regarding the stability of some vehicles during avoidance manoeuvres. Since the driver model will be used to assist in ensuring that all drivers experience good handling, the driver's goal needs to be modelled. It is the driver's goal that motivates him or her to turn the steering wheel. Thus, differences in goal between drivers produce differences between steering styles, which in turn results in differences in the vehicle's path. However, most of the existing driver models that were evaluated required the driver model to follow a pre-defined path.

Much early, published work on driver modelling centred around the concept of the crossover model [21]. This model characterises the driver/vehicle combination in control engineering terms [22]. The crossover model has its origin in regulatory tasks, such as those involving crosswind disturbances. An attempt to use this model to simulate manoeuvres was rewarded with only limited success [23]. The crossover model differs from a real driver in that it does not utilise preview; that is, information about the path ahead of the vehicle.

A different approach, a two-level model of driver steering behaviour [24], divides the driver's steering task into guidance and stabilisation. The guidance task is in response to feedforward information of the road ahead. The stabilisation task is to correct for any deviations from the "desired path" and the vehicle's actual path. In this driver model, the "desired path" is defined as curvature of the path with respect to time [24]. Thus, the driver model acts as a path follower.

A mathematical technique that conforms to the two-level concept, optimal preview control, has been applied to driver modelling in the form of preview control [25, 26]. Like the two-level concept, optimal linear control includes feedforward and feedback control. Optimal preview control is used to determine the optimum control input, that which minimises a weighted sum of path error over the preview distance. Preview of around one second ahead [27] has been found to produce satisfactory results when applied to a path following task.

A commercially available driver model, IPG Driver[1], was reviewed. This model achieves maximum speed round a track by learning the maximum tyre slip angle that is possible through each corner. This driver model represents an optimum driver rather than a typical customer.

In summary, many existing driver models were rejected because they require either the user to specify a precise path for the driver model to track [22, 25, 28, 26] or the driver model programme itself calculates a path that it will track [29]. This does not allow for the vehicle's path to be determined by the driver's own goal. Other driver models were rejected because they require data from a driving simulator for their formulation [30, 24, 31, 32]. This data is not available at the early stages of vehicle design at which the driver model is intended to assist.

It became clear that a new driver model would have to be developed, one which does not constrain the driver model to track a pre-determined path.

4.4.2 Driver Modelling Techniques

A literature review of the various methods used to model different aspects of the driver was undertaken to provide guidance for the development of a new driver model.

In the literature review of Submission 5, the inputs to the driver model were considered. Many driver models use only one or two inputs. Lateral position error and heading angle are common inputs [33, 34, 22]. However, tests have shown that yaw rate and lateral acceleration affect drivers' evaluation of vehicle handling [35] and, therefore, have the potential to affect a driver's steering input. Thus, it was proposed that the inputs to the driver model include vehicle motion. This provides the opportunity for the driver model to adjust the steering input to suit each vehicle's dynamics.

It was recognised that a large number of inputs to the driver model tends to increase its complexity. Whereas a model that uses a cost function to

[1] IPG Driver from IPG Automotive Software and Consulting GmbH.

combine several inputs to the driver into one measure [34] is more manageable. Alternatively, a neural network can potentially be used to efficiently process a large number of inputs [36].

4.4.3 Formulation of a New Driver Model

The driver model was developed in three stages. The first stage utilised optimal control theory with the solution calculated iteratively. This approach is presented in detail in Submission 10 (the SAE paper) and Submission 11. The optimal control driver model successfully simulates the behaviour of real drivers over a lane change manoeuvre. However, this method of calculation is very slow, which discourages its use over longer or more complex manoeuvres. Therefore, data generated by the optimal control driver model was used to train a neural network. It was intended that the neural network driver model would then be capable of negotiating a wider range of driving situations. However, the performance of the neural network driver model was found to be unsatisfactory, as is reported in Submission 12. Finally, linear optimal control theory was employed, which does not have to be solved using the slow, iterative procedure. This method can only be used in conjunction with a linear vehicle model but, nevertheless, successfully represents real drivers' steering styles. In fact, the linear optimal control driver model is as successful as the optimal control driver model in mimicking real drivers and has the advantage of solving in under thirty seconds when using MATLAB. The linear optimal control driver model is presented in Submission 13 and its development is summarised here.

The theory of optimal control is used to find the control input (steering wheel angle in this case) that minimises a given cost functional [37, 38]. This method was selected for driver modelling because the cost functional presents a means of representing and adjusting the driver's goal. The cost functional consists of a weighted combination of driver steering input and vehicle motion and path predicted from a dynamic vehicle model. The dynamic vehicle model and the cost functional has a family of optimal control solutions which determine the paths that are taken through the single lane change manoeuvre. An individual choice of the relative weightings on driver effort and vehicle motion defines a particular path through the manoeuvre.

Optimal preview control has been used in earlier driver models, as discussed in section 4.4. However, optimal control is used here to enable the driver model to generate a path through a course rather than to follow a pre-defined path. Furthermore, the preview control driver models look-ahead around one second whereas the driver model developed here determines the optimal control input over the entire manoeuvre. This is in accordance with the vehicle test results of section 4.3, which clearly show that the driver steers towards the second lane a minimum of three seconds before reaching the first cones that define the lane. In addition, the cost functional used here includes the facility to have cost on the vehicle's motion; the preview control driver models do not.

The optimal control driver model successfully simulates different drivers negotiating a single lane change. The course is shown in figure 8, it is the same course that was used for the vehicle tests reported in Submissions 8 and 9. The figure also shows Y_d, which defines the required step change in lateral lane position and the orientation of the two lanes. Over the middle section of the lane change, Y_d is not defined. Thus, Y_d is information on where the two lanes lie rather than a definition of a path to be tracked. Function Y_d is used to derive an error in lateral position and in heading angle for inclusion in the cost functional. A piece-wise function (α) is used to enable a different cost to be placed on the second lane than the first lane. Parameters τ_1 and τ_2 extend Y_d beyond the coned lanes. In this way, Y_d represents the driver's desire to clear the first set of cones before beginning to change lanes and to line the vehicle up with the second lane in good time. The other parameters in the cost functional are weights on lateral velocity, yaw rate, roll angle and roll rate.

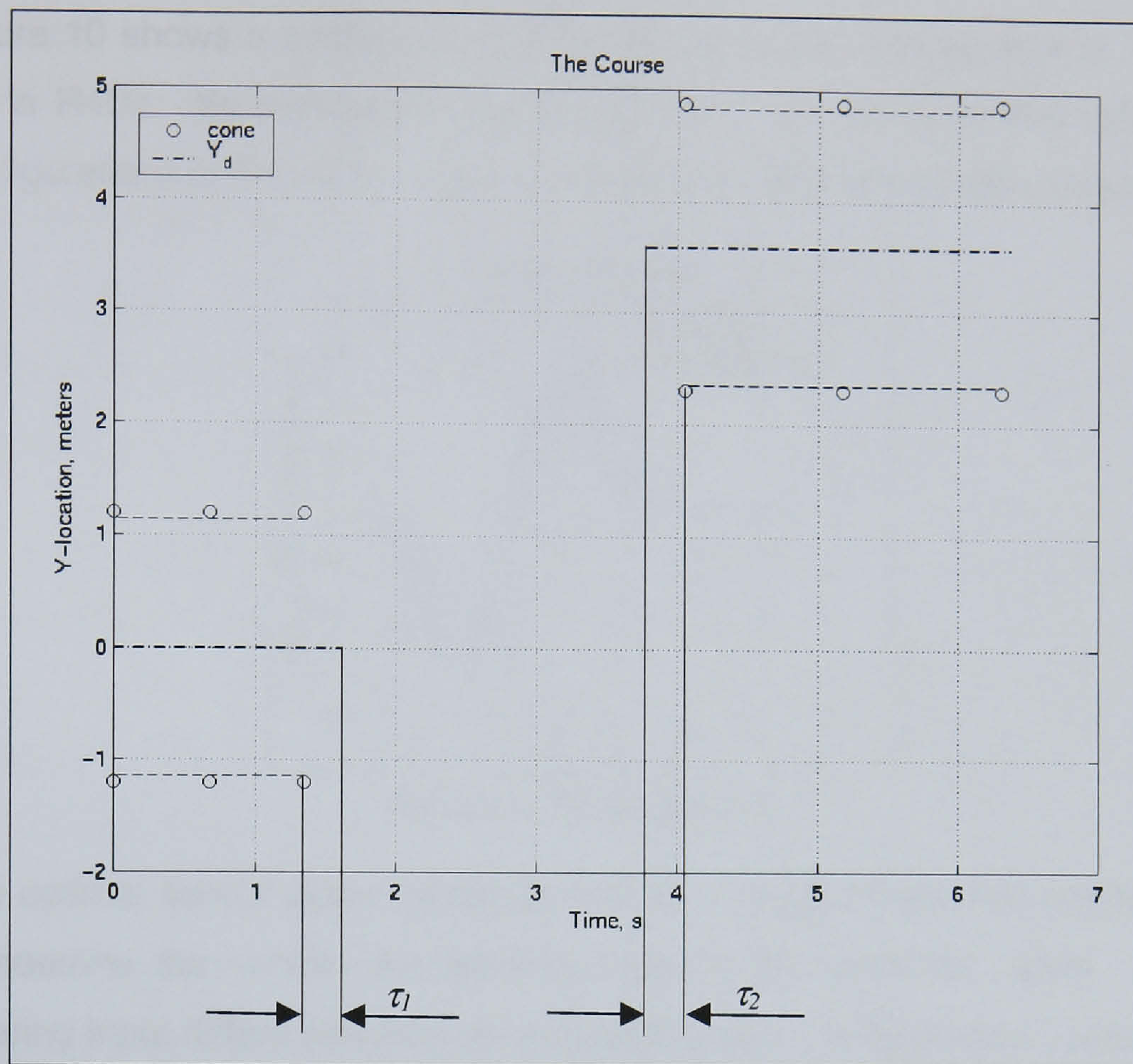

Figure 8. The Course.

4.4.4 Simulations using the Driver Model

A number of configurations of the cost functional parameters have been determined which enable the driver model to represent two drivers in vehicles R400 and L25. The two drivers represented are JG and TC, the drivers at the extremes of the range of test results. Figure 9 shows the example of the driver model configuration that mimics driver TC in R400 over the single lane change.

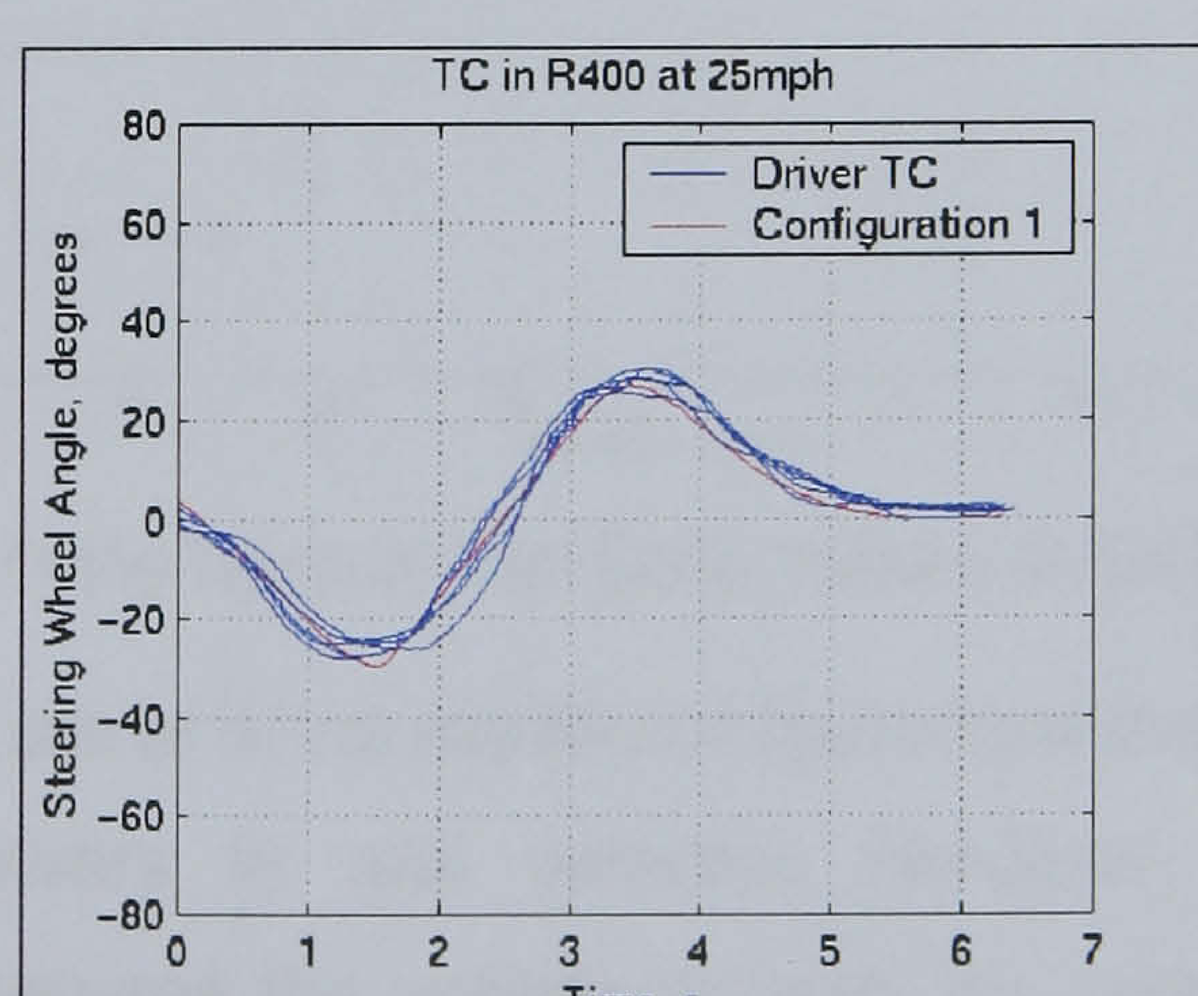

Figure 9. Steering Inputs.

Figure 10 shows a configuration of the driver model that represents driver JG in R400. By comparing figure 9 to 10, it can be seen that different configurations of the driver model generate very different steering inputs.

Figure 10. Steering Inputs

The optimal control driver model generates a range of steering inputs that manoeuvre the vehicle successfully through the specified lanes. This steering input differs between drivers, as it does in vehicle tests. Likewise, the vehicle path generated by the driver model varies between configurations representing different drivers, as figure 11 demonstrates.

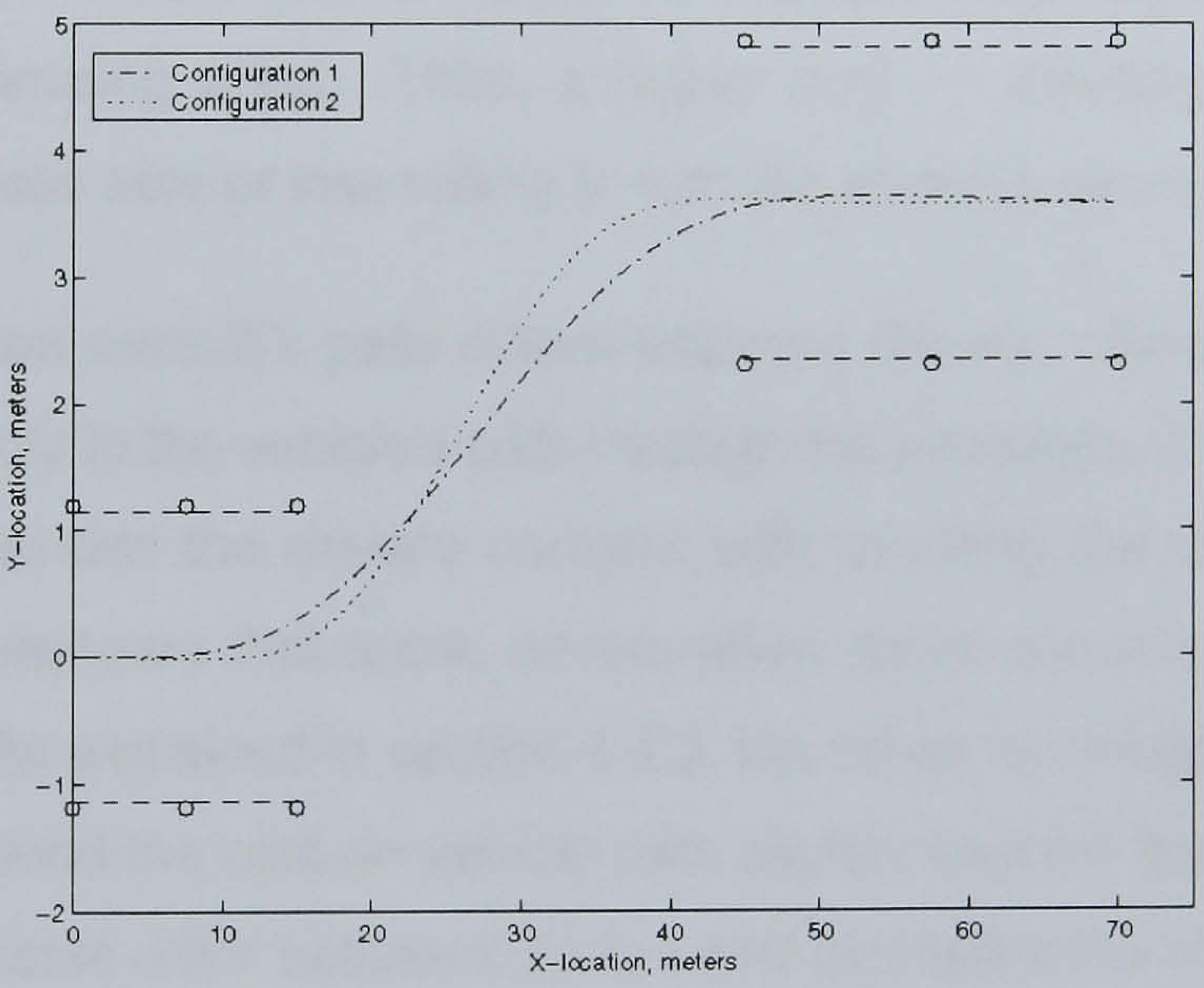

Figure 11. Paths Taken by Two Configurations of the Driver Model.

The results shown are of driver model configurations that match the steering inputs of real drivers in real vehicles. However, any solution that successfully manoeuvres the vehicle through the coned course could be used by a real driver. Hence, the driver model can be used to predict driver behaviour in concept vehicles, as originally intended.

4.5 Discussion of Drivers' Steering Behaviour

The literature review of human factors, the vehicle tests and the development of the driver model have all added to the understanding of drivers' steering behaviour.

The vehicle tests showed that drivers do not adapt their steering inputs to take account of a reduction in vehicle roll afforded by an active chassis control system. This was corroborated by the realisation that the driver model configurations that represent real drivers have zero cost on roll angle and roll rate. Similarly, in the tests, each individual driver scales his or her steering input only to accommodate a difference in steering ratio between vehicles and not in response to the change in vehicle motion. Correspondingly, the costs on lateral velocity and yaw rate in the successful driver model configurations are zero. The non-zero costs concern only steering magnitude and the vehicle's path. The cost on steering magnitude differs between drivers and is thought to represent the importance, to the driver, of minimising effort. Thus, a higher cost on steering represents a driver who is less able or less willing to turn the steering wheel.

The cost on the vehicle's path differs between drivers. Since the cost on path relates only to the vehicle's path through the two lanes, it is thought that this cost represents the driver's concern with avoiding the cones marking the lanes. It appears that some drivers show more concern in this sense than others. As explained in section 4.4.3, the driver model parameters can be used to extend the cost on vehicle path slightly beyond the coned lanes. These parameters differ between drivers and represent the extent to which the driver wants to ensure that the vehicle will not clip any cones during exit from the first lane or entry to the second lane.

There are analogies between the mathematical structure of the driver model and the human task of driving. The solution of the linear optimal control problem that has been used to formulate the driver model includes a feedforward signal, which is generated by the signal that defines the required manoeuvre. In the driver model, this multi-channel signal is dominated by a channel corresponding to heading angle, closely followed by a channel corresponding to lateral position error. It is commonly accepted that lateral position error and heading angle are salient driver inputs [33, 34, 22]. It is now suggested that drivers may rely most heavily upon heading angle information.

The vehicle tests showed that each individual driver uses essentially the same steering input in different vehicles and at different speeds. The driver simply scales his or her steering input to take account of the steering ratio and with respect to time, respectively. It was thought that this could mean that any one driver steers so as to follow the same path through the manoeuvre, regardless of vehicle or speed. The path of the vehicle could not be tracked during the tests. Instead, the driver model was used to study the path taken by different drivers. This produced no conclusive evidence that an individual driver steers so as to follow the same path in every vehicle and at every speed. In addition, it was found that a different configuration of driver model parameters is required for each driver, vehicle and speed. Thus, neither the driver's goal nor the vehicle's path seems to be a constant.

It is hypothesised that the constant between vehicles and speeds is a pattern of steering input, unique to each driver. It is likely that, like walking and writing, steering is performed using a programmed pattern of movements. It has been shown that humans repeat patterns of movement when walking or writing that have the same proportions in time and space, regardless of the size or speed of the movement [39]. That is, the ratios of the times at which the major features of the pattern occur remain the same. Similarly, the ratios of the magnitudes of the major features are unchanged by varying the overall size or speed of the movement. This is precisely what was exhibited by each individual driver. Hence, it is hypothesised that feedforward information on the required heading angle and lateral position through the course is used to summon, from the brain, the appropriate pattern of steering. The pattern is then scaled to accommodate the particulars of the vehicle's dynamics and the speed. Feedback is then used by the driver to correct errors in the response of the vehicle to steering inputs (due to inescapable sources of variability) and is independent of the manoeuvre itself.

If the concept of steering patterns is accepted, then the differences between drivers are due to differences in their stored patterns. These patterns are established over time, through learning, and then stored. This is akin to the experience of most drivers; when learning, one operates on a conscious level and, over time, driving becomes a sub-conscious activity that is stored away and can be called upon at any time. It is likely then that the driver's goal influences the learning process and the stored pattern more than it does each individual manoeuvre, which would explain why the model of any one driver's goal was not constant between vehicles and speeds.

4.6 Application

The knowledge gained about driver behaviour and the driver model are applied, in Submission 14, to the development of a variable damping switching strategy that enhances vehicle handling.

Variable dampers have been used previously to improve ride quality [2]. Generally, a "soft" (low) rate is required for ride comfort over road inputs whereas a "firm" (high) rate is needed to limit the roll of the vehicle in response to steering inputs. Figure 12 illustrates the characteristics of a particular set of variable dampers. The dampers can provide any rate between the extremes of "firm" and "soft" shown. In addition to the ride benefits, variable dampers have the potential to modify vehicle handling because they can control the lateral and longitudinal load transfer characteristics of the suspension during transient movements [3]. A preliminary investigation was undertaken, using the driver model, in order to ascertain whether or not this effect would be beneficial to drivers during typical driving situations.

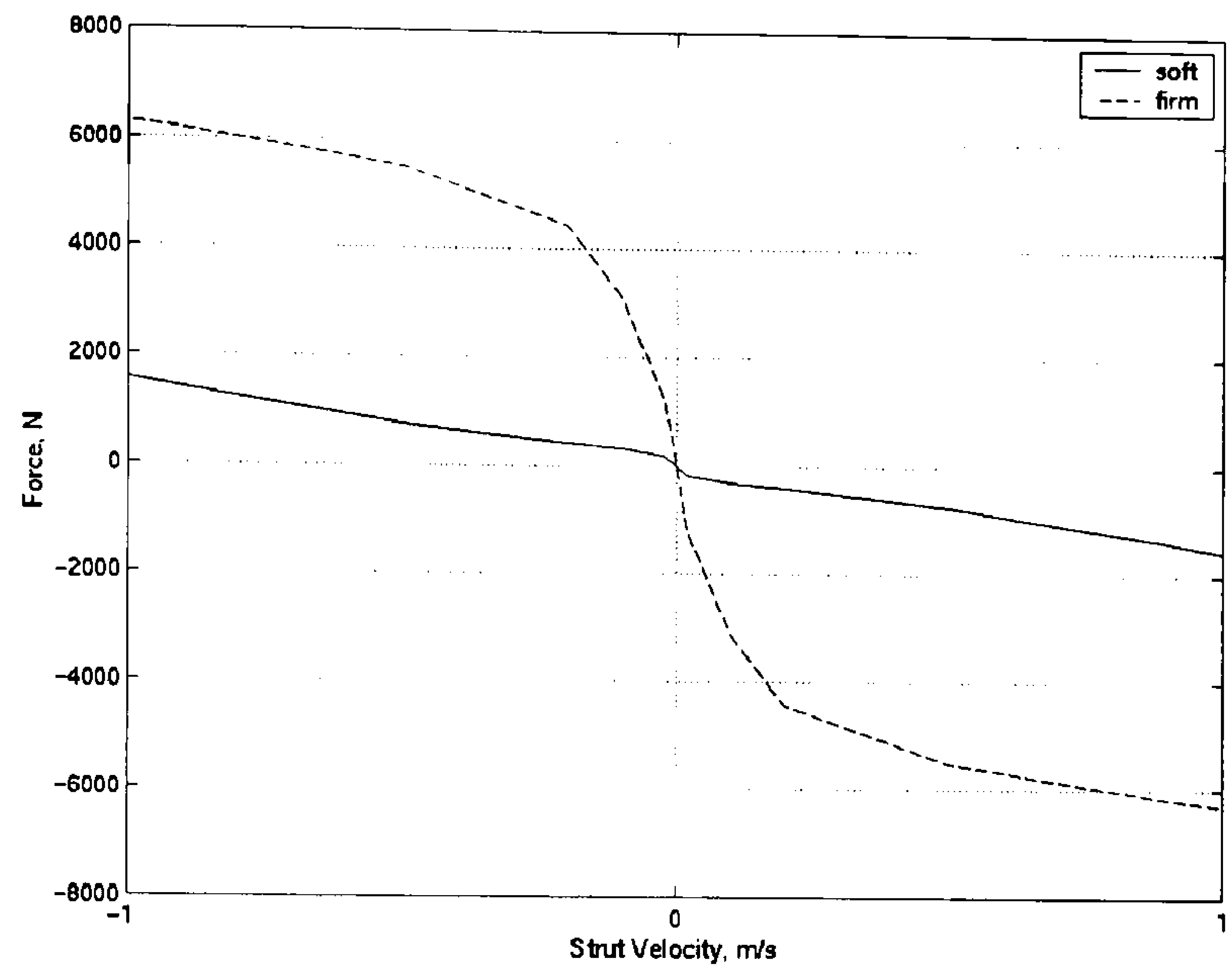

Figure 12. Damper Characteristics

The vehicle and variable dampers are modelled in the Simulink environment; non-linear tyre models are included. The variable dampers are proposed for a concept vehicle that has similar proportions to L25. Therefore, the steering inputs generated by the driver model that have been validated against the tests in L25 are used. It is found that the steering inputs representing those of drivers JG and TC enable the vehicle model with variable dampers to be manoeuvred successfully through the single lane change at 35mph.

The influence of dampers on handling is compared to the influence of the stiffening of the rear anti-roll bar by 50% because this is known to noticeably modify handling characteristics. Specifically, stiffening the rear anti-roll bar increases the oversteer tendency of the vehicle [40]. Oversteer is when a vehicle assumes a "nosed-in" attitude when cornering. Conversely, an understeering vehicle takes a path of greater radius given the same steering angle as an oversteering vehicle and has a "nosed-out" orientation when cornering (also called "ploughing"). Oversteer is indicated by slip angles at the rear tyres that are larger in magnitude than those at the front [41].

Figure 13 demonstrates that putting variable dampers (trace "R=firm") onto the standard vehicle has a greater potential than the stiffer rear anti-roll bar (trace "R=stiff") to increase oversteer tendency through a lane change manoeuvre.

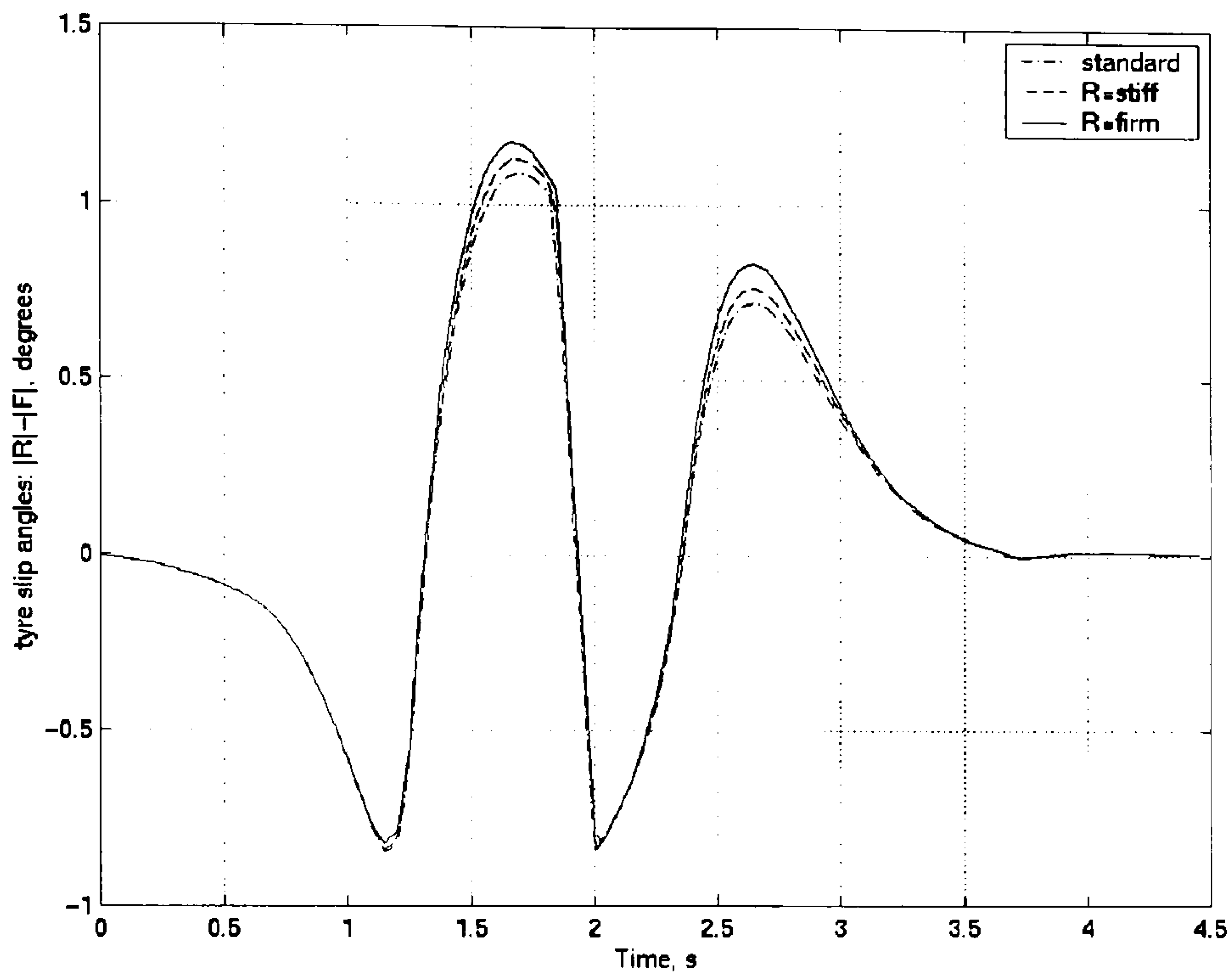

Figure 13. Tyre Slip Angles during a Lane Change (JG at 35mph).

Of course, simply putting firm dampers on the rear of the vehicle deteriorates ride quality. In addition, an increase in oversteer tendency is not desirable in all situations because it can make the driver feel less sure of the vehicle, as if the rear end of the car is about to spin out [40]. Thus, a switching strategy has been developed that increases the responsive feel by switching the rear dampers to firm upon turn-in and then switches the front dampers to firm at a later moment. When all dampers are set to firm, the initial increase in oversteer tendency is eradicated. Additionally, this further reduces body roll. Finally, during straight-ahead driving, all dampers are switched to soft to give good ride quality.

Figure 14 illustrates the change in oversteer tendency afforded by the switching strategy.

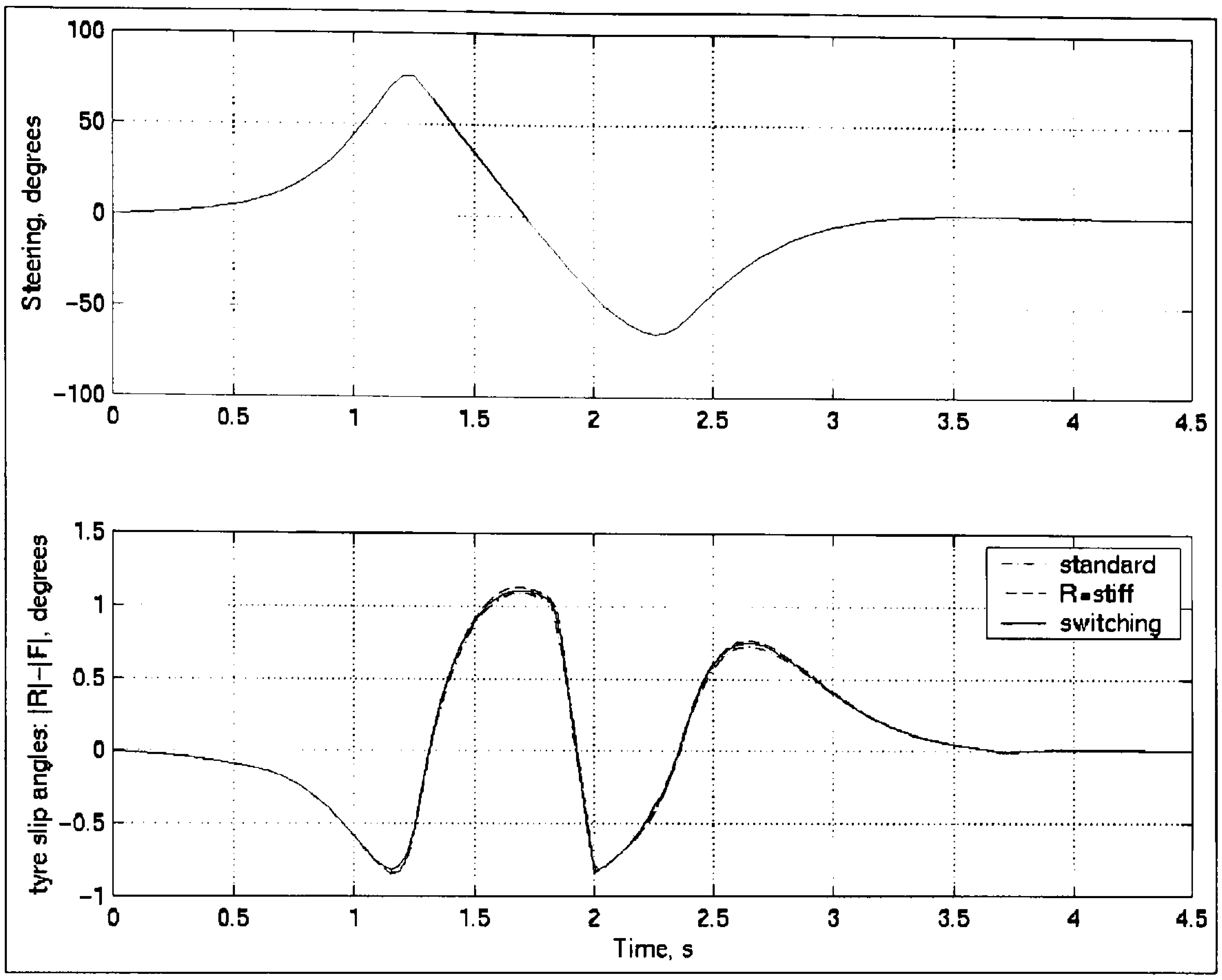

Figure 14. JG at 35mph

Figure 15 shows more clearly the oversteer/understeer of each vehicle configuration at the trough at 1.2 seconds. The standard vehicle understeers and each of the two different vehicle configurations serve to reduce this understeer; that is, increase its oversteer tendency. At this time, upon turn-in, the switching variable dampers provides a greater increase in oversteer tendency than the stiff rear anti-roll bar.

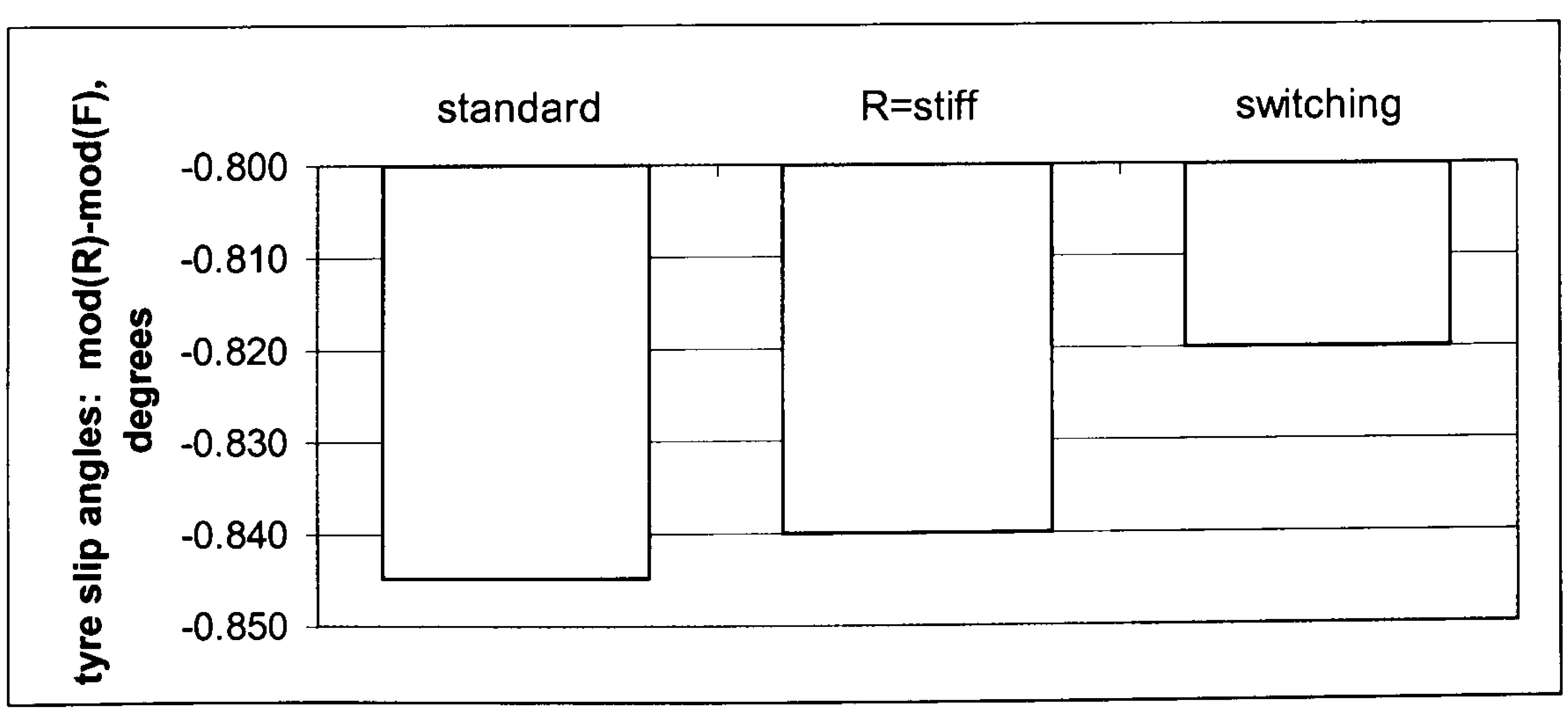

Figure 15. JG at 35mph, Trough at 1.2 seconds.

Figure 16 shows the oversteer/understeer of each vehicle configuration at the peak at 1.7 seconds; that is, during the mid-stage of the lane change. In contrast to the characteristic at turn-in, here, switching variable dampers provides a lesser increase in oversteer tendency than the stiff rear anti-roll bar. Nevertheless, the oversteer tendency of the switching variable dampers is still greater than that of the standard vehicle.

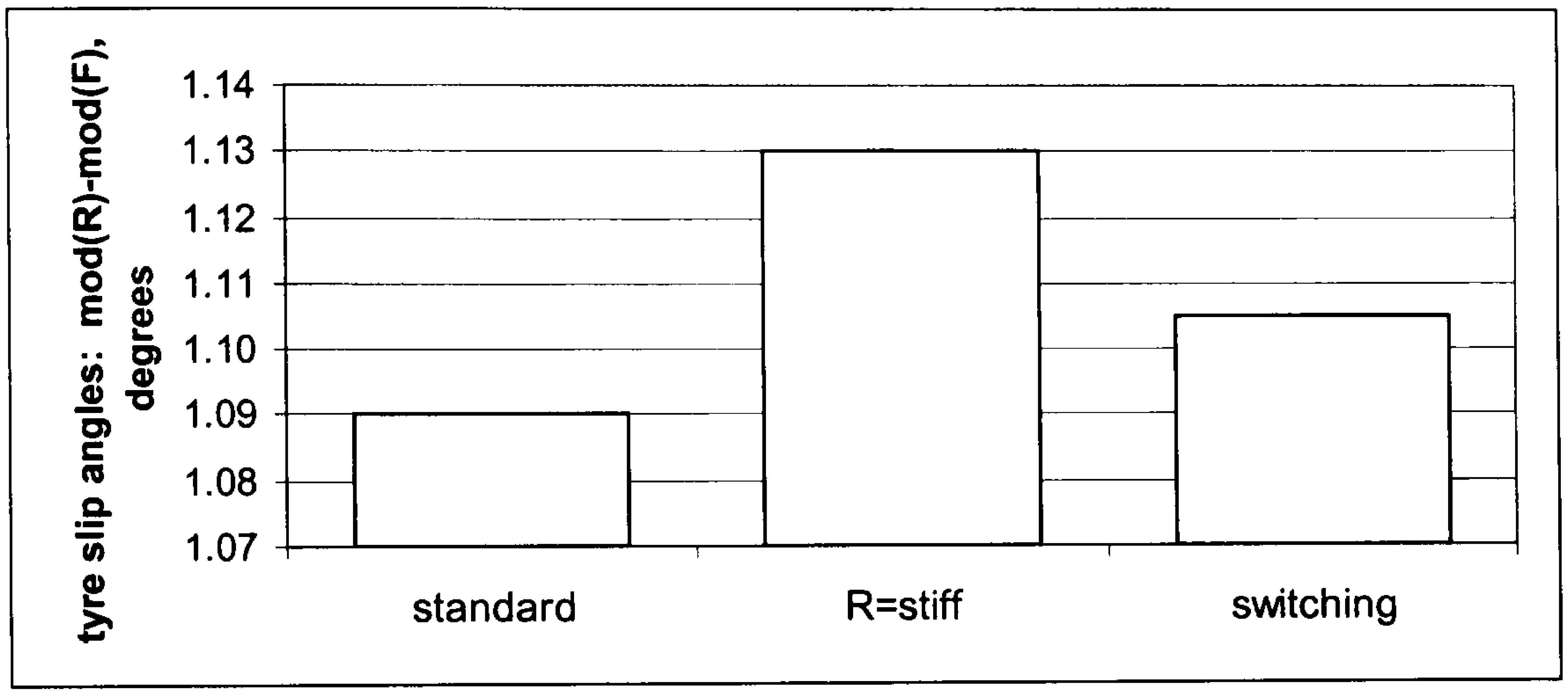

Figure 16. JG at 35mph, Peak at 1.7 seconds.

Figure 17 confirms that the use of the switching strategy reduces the roll angle experienced by JG to almost the level of having all dampers set to firm. That is, the switching strategy operates almost to the full potential of the variable dampers, in terms of roll angle reduction. However, unlike when all dampers are firm, switching allows the vehicle to return to a position of zero roll fairly quickly. Switching also reduces the roll rate experienced by JG over that of the standard vehicle. The sharp "knees" of roll rate are caused by the instantaneous switching of the dampers rates in this vehicle model. The real variable dampers would, necessarily, have smoother switching characteristics.

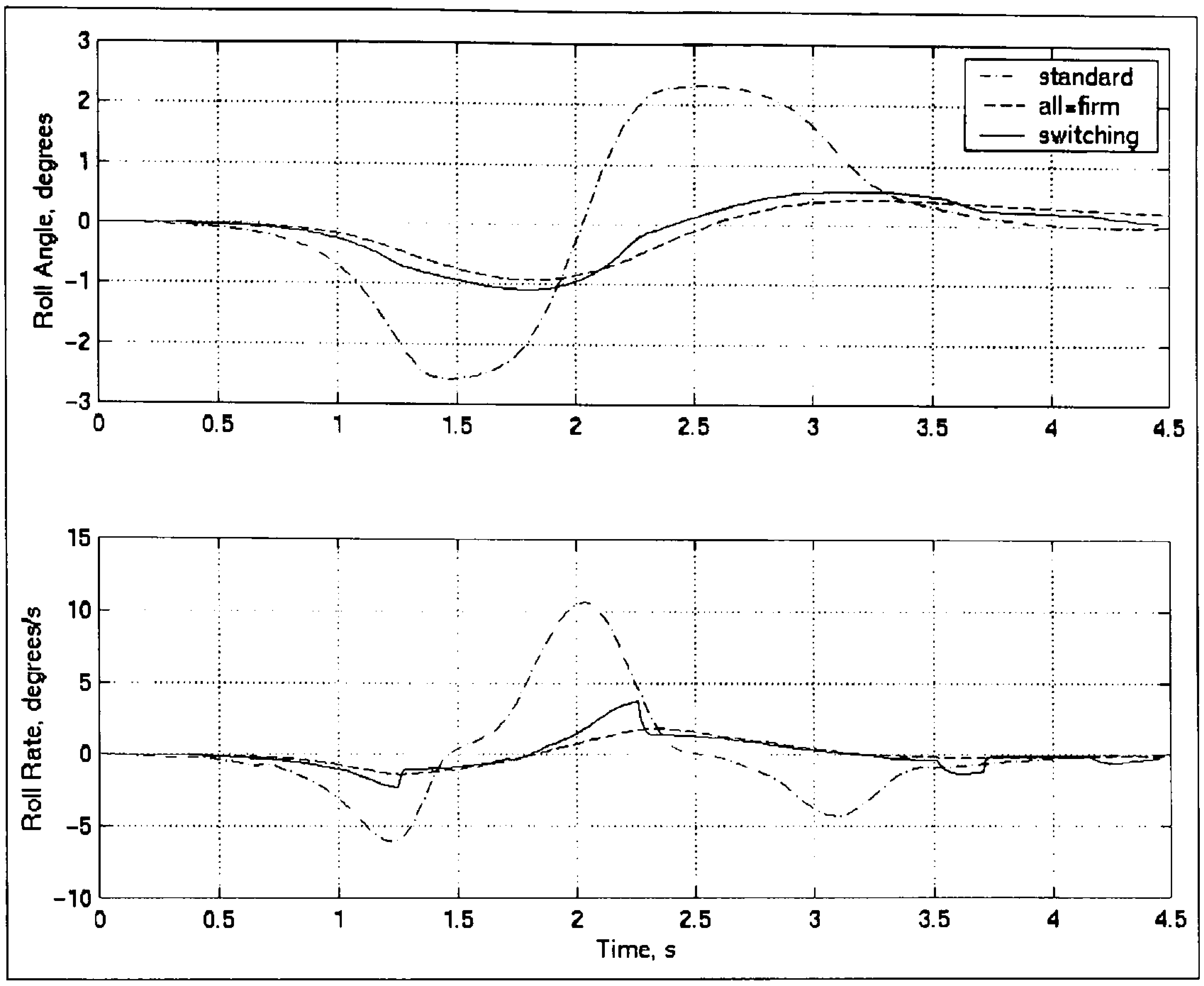

Figure 17. JG at 35mph

Figure 18 verifies that driver TC also enjoys reduced roll angles through the lane change with the switching variable dampers. However, because TC uses smaller steering inputs to complete the manoeuvre, the reduction in roll angle afforded to him is less than the reduction that JG experiences.

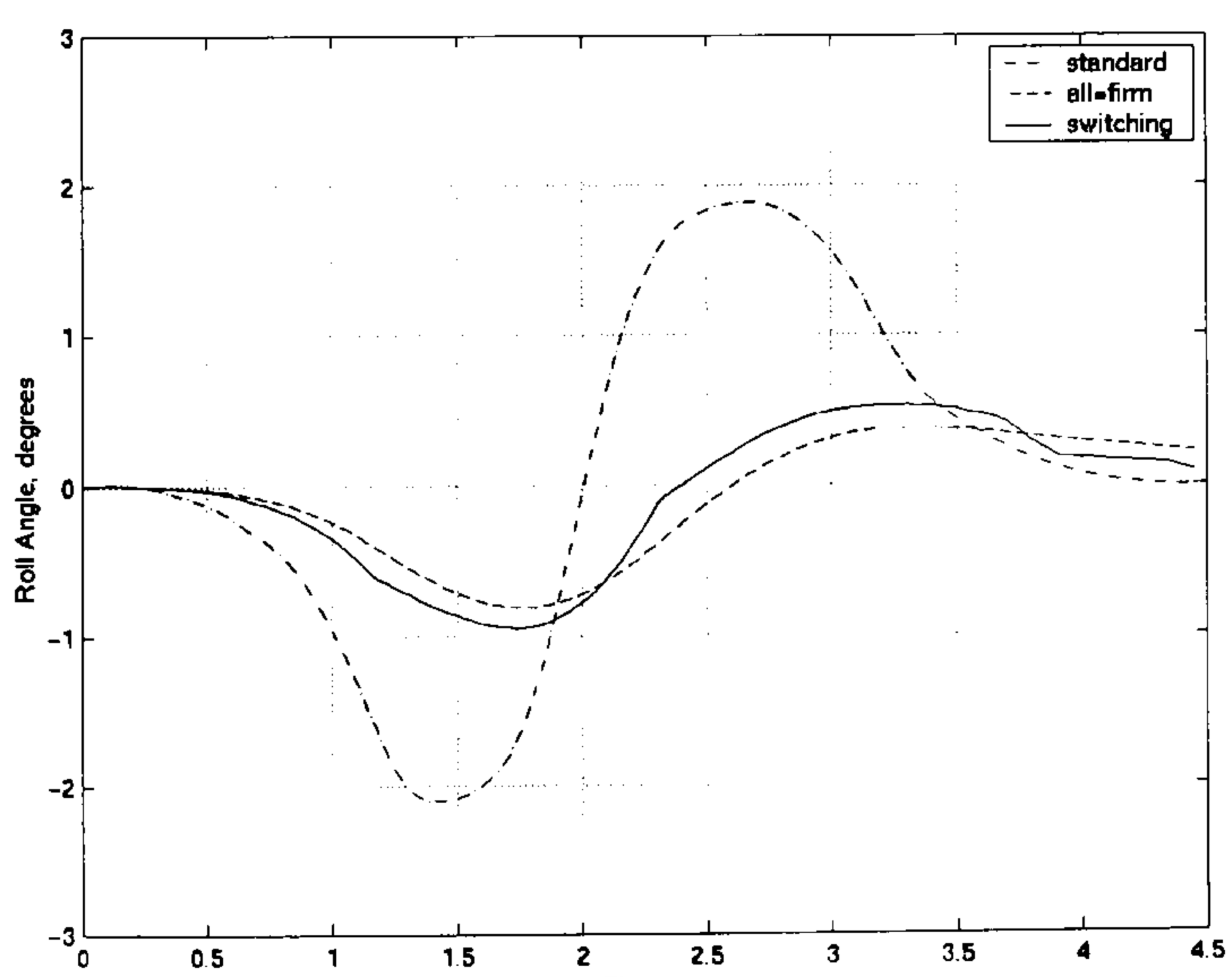

Figure 18. TC at 35mph

Section 4.5 explained that each driver scales his or her steering pattern with respect to time when the speed of the manoeuvre changes. Hence, the steering inputs of JG and TC at 35mph were scaled to enable negotiation of the lane change at 55mph. Naturally, the magnitude of the steering inputs also had to be scaled to enable the same width of lane change to be completed. Figure 19 shows an example of how JG's steering has to change from 35mph to 55mph to enable the course shown in figure 2 to be negotiated.

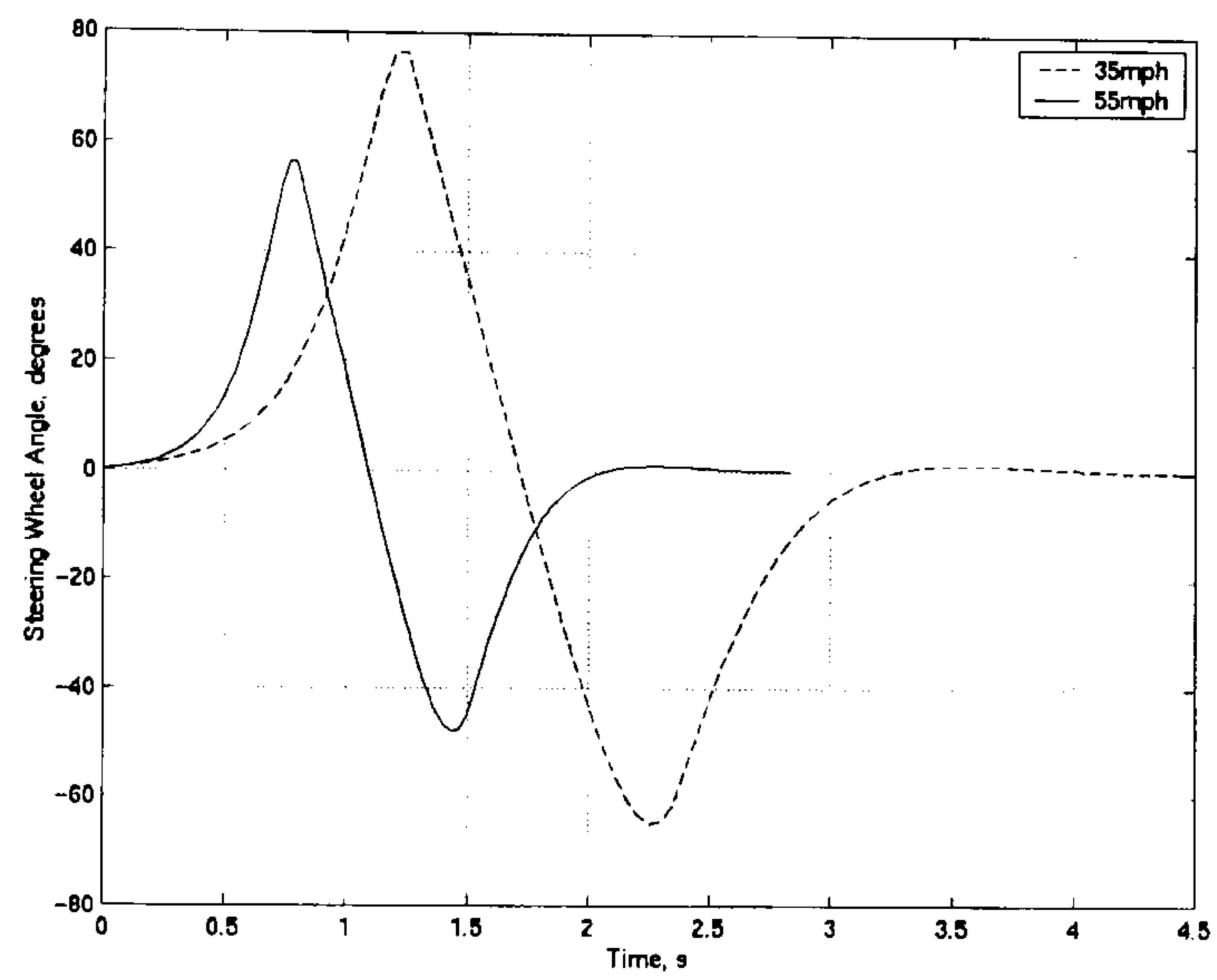

Figure 19. JG Steering Inputs.

The magnitude scaling factors required for JG and TC to negotiate the lane change 55mph are presented in the third column of table 1; that is, the factor by which the magnitude of the 35mph steering input (in the standard vehicle) is scaled in order to allow the lane change to be negotiated at 55mph. The standard vehicle requires the drivers to change their steering inputs the least. Switching the variable dampers requires the drivers to change their steering inputs a similar amount as when the stiffer anti-roll bar is put onto the rear. This suggests that drivers will not be perturbed by the scaling required when driving the vehicle with variable dampers. The fourth column of table 1 compares the magnitudes of the steering inputs required at 55mph. For example, the driver model representing JG in the vehicle with a stiffer anti-roll bar on the rear makes a steering input 5.1% smaller than when in the standard vehicle. For both drivers, switching the variable dampers enables the lane change to be negotiated at 55mph using smaller steering inputs than they would use when in the standard vehicle.

Driver	Vehicle Configuration	Magnitude Scaling	Reduction in Steering Magnitude
JG	standard	0.778	JG's baseline
JG	R=stiff	0.738	5.1%
JG	switching	0.725	6.8%
TC	standard	0.803	TC's baseline
TC	R=stiff	0.768	4.4%
TC	switching	0.758	5.6%

Table 1. Scaling of steering input required to complete the 3.59m lane change at 55mph.

Simulations of JG and TC negotiating the lane change at 55mph confirm benefits of the variable dampers and do not reveal any problems at this higher speed.

4.7 Conclusion

It was explained that the analysis and simulation of drivers' steering behaviour was undertaken in response to business requirements. It was predicted that, in the future, customers will require vehicle handling that suits their own style of driving. It was recognised that there is an opportunity to provide this with the use of active chassis control systems. However, in order to develop such systems to provide enhanced handling on the customer's first test drive and on every journey thereafter, a better understanding of drivers' steering behaviour was required.

Insufficient data on steering behaviour was found in the literature so vehicle tests were conducted. It was found that there is a significant difference between the steering input that any two drivers make through the same course. The scale of this difference and its effect on the vehicle motion experienced by each driver was quantified. Furthermore, it was found that each individual driver seems to have a unique pattern of steering that they repeat every time they encounter a given manoeuvre (a single lane change in this case). This pattern is simply scaled with respect to time and/or magnitude to allow the manoeuvre to be negotiated in different vehicles or at different speeds. This is similar to the patterns of movement that humans repeat when walking or writing.

In order to incorporate these revelations about drivers' steering behaviour into the analysis of concept vehicles, a driver model was formulated that represents different drivers manoeuvring through a single lane change course. The application of this driver model to the development of a switching strategy for variable dampers was then described. It was useful to be able to simulate a realistic driving situation since the aim for the variable dampers is to enhance handling during regular driving situations.

The driver model enabled congruent driving situations to be compared. The use of the appropriate steering inputs enabled the motion of each vehicle configuration as it is driven through the lane change to be compared. This is in contrast to traditional tests where the vehicle's forced response to a given steering input is evaluated. It was demonstrated that the variable damper switching strategy, developed with the aid of the driver model, has multiple benefits that are experienced by the driver. It was shown that responsive feel upon turn-in is increased and roll and roll rate are reduced without compromising the ride quality during straight-ahead driving. Moreover, the simulations showed that, at 55mph, switching the variable dampers enables the drivers to negotiate the lane change using smaller steering inputs than when in the standard vehicle. It is hypothesised that this reduction may be perceived as a benefit by drivers.

5 Innovation Report

The objective of the Engineering Doctorate programme is to develop engineers who are capable of innovating and managing innovation within the competitive business environment. Therefore, the degree of Doctor of Engineering is awarded to those candidates whose portfolios of research demonstrate innovation in the application of knowledge to the engineering business environment. The following statements of innovation are made and will be justified in the following sections.

1. Quantification of the differences between drivers' steering styles.
2. Formulation of a driver model that generates its own path, rather than attempting to track a pre-defined path.
3. Formulation of a driver model that represents different steering styles as exhibited by real drivers.
4. Development of a variable damper switching strategy.
5. Identification of the primary causes of steering veer through the creation of the vector forces and moments model.
6. Application of Taguchi's Design of Experiments to simulation using ADAMs for efficient use of the time-expensive multi-body simulation.
7. Analysis of the patented [1] Mechanically Interlinked Suspension system.
8. Definition of a method for simulating cross-axle articulation for measurement in ADAMs.

5.1 Quantification of the differences between drivers' steering styles

Differences in the steering inputs of different drivers through the same course have been identified previously by Willumeit [19]. In addition, Breuer [20] measured the steering angles made by drivers through a lane change course. However, in the tests by Breuer, the drivers were allowed to select the vehicle's speed and brake during the manoeuvre. The variation in vehicle speed necessitates a variation in steering angles between drivers to enable all of them to complete the course. In contrast, the differences in steering styles between drivers, uncorrupted by variations in vehicle speed, have not been quantified before. In addition, the effect of different vehicles and active chassis control systems on steering styles has not been quantified previously. This data, presented in Submissions 8 and 9, has been communicated within the company. The evidence that a driver's steering style influences the benefit afforded to him or her by handling enhancements is now taken in to account when the business is considering the cost versus benefit of implementing active chassis control systems on new vehicles.

5.2 Formulation of a driver model that generates its own path

Optimal control theory has been used to create a driver model that negotiates a lane change without the user having to define a path for the driver model to follow. Publications show that existing driver models track pre-defined paths, as was discussed in section 4.4.

5.3 Formulation of a driver model that represents different steering styles

The driver model presented in section 4 has been shown to simulate the steering behaviour of real drivers. Vehicle tests revealed that different drivers exhibit different steering styles through the same course. Similarly, the driver model generates a range of different steering inputs that manoeuvre a vehicle model successfully through a specified course.

5.4 Development of a variable damper switching strategy

A switching strategy for variable dampers was developed using the driver model. Existing switching strategies are primarily aimed at enhancing vehicle ride in the vertical sense and reducing roll in response to steering inputs [2, 42]. In contrast, the switching strategy developed in Submission 14 is aimed at enhancing the handling of the vehicle by increasing the feeling of responsiveness when the driver turns-in at the start of a manoeuvre. Although not yet tested on a prototype, simulations show the switching strategy to be as significant, in terms of modifying of handling balance, as increasing the stiffness of the rear anti-roll bar by 50%. In addition, the switching strategy achieves this whilst still reducing roll in response to steering inputs. This switching strategy is being further developed.

5.5 Identification of the primary causes of steering veer

Steering veer is a problem that blights many production vehicles. Land Rover engineers cited over forty factors that could cause the problem, including, for example, anti-roll bar pre-load, tyre properties and suspension geometry. In addition, many of the forty factors interact to make the problem worse. In contrast, previously published research focuses only on the influence of wheel alignment and tyre characteristics on veer [43].

The complexity of the problem meant that it had not been modelled successfully before. The author formulated a mathematical model of the problem and simulated it over four thousand times, each time with a different combination of factors. This enabled three major causes of veer in the vehicle in question to be identified and actions were taken to rectify the vehicle. This model has since been used to assist with similar problems on other vehicles.

5.6 Application of Taguchi's Design of Experiments to Simulation using ADAMs

A Taguchi array of experiments was used in conjunction with a multi-body systems simulation software package (ADAMs). This reduced the time taken to investigate the effect of four design parameters on the handling of a novel suspension design by 88%. Such Design of Experiments methods are not used when analysing traditional suspension systems because there is sufficient historical knowledge to enable heuristic optimisation.

5.7 Analysis of the patented Mechanically Interlinked Suspension

The author performed handling analysis on a patented [1] suspension system. This innovative design was applied to one of the company's new vehicles. The author's role in the project was to investigate the optimisation of the design for both off-road and on-road performance.

5.8 Definition of a method for simulating cross-axle articulation for measurement in ADAMs.

Mechanically Interlinked Suspension improves off-road performance by increasing cross axle articulation; that is the flexibility of the suspension in the situation illustrated in figure 20.

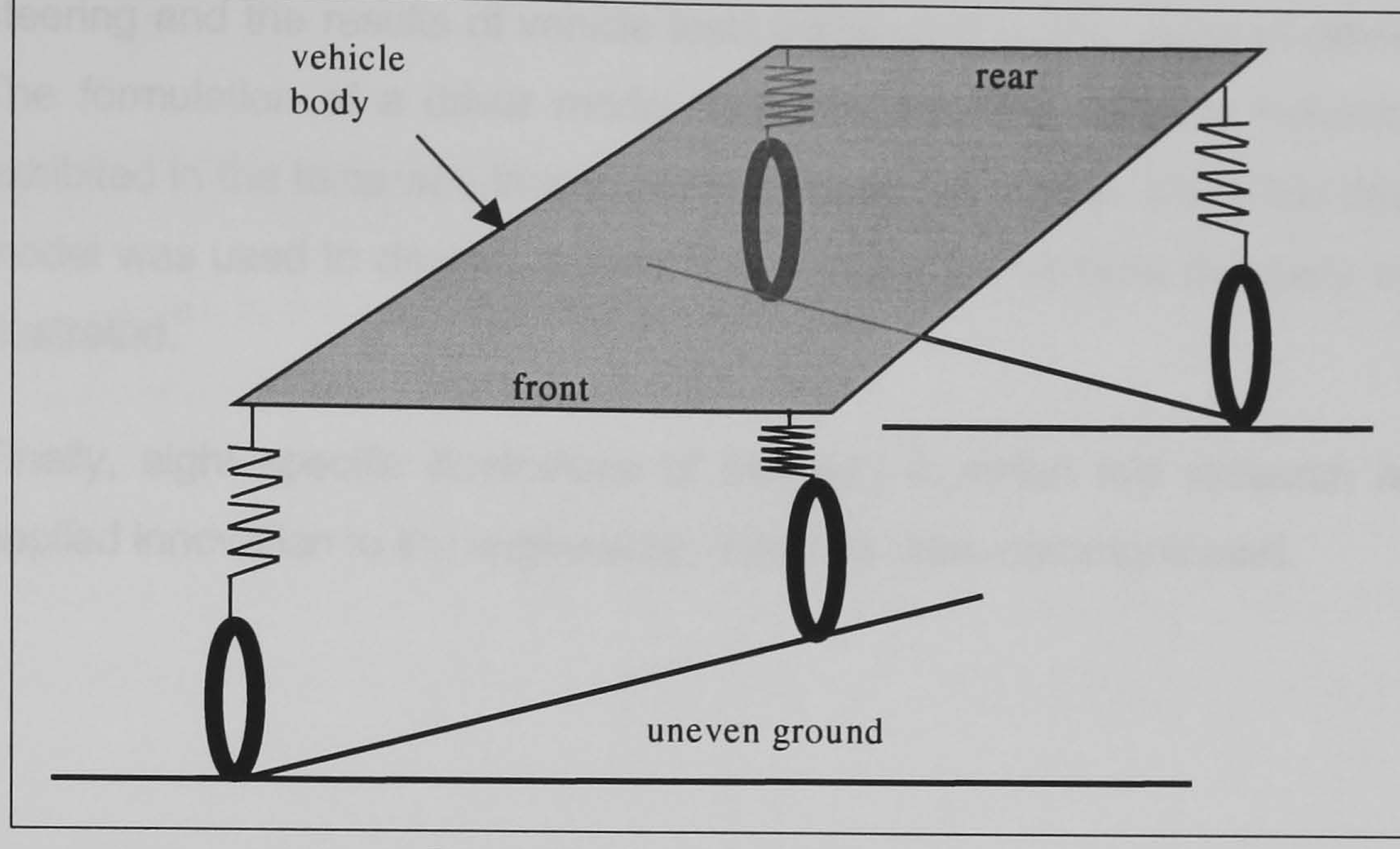

Figure 20. Cross Axle Articulation.

The author defined a method that enables cross axle articulation to be quantified from a multi-body systems simulation (ADAMs) of the suspension. If a prototype of the suspension is available, the cross axle articulation is measured by raising diagonally opposite wheels in a ratio that keeps the vehicle body level. Thus, this is a closed-loop test. Such a test would be very complex to recreate in ADAMs. Instead, the author defined a procedure for an open-loop test that is easily simulated. It is demonstrated in Submission 7 that, for the particular vehicle model in question, this method is sufficiently representative of the closed-loop test.

6 Conclusion

In this document, research into the modelling and analysis of current and concept vehicles for the purpose of enhancing vehicle handling was summarised. This work is detailed in fifteen reports that have been submitted to a portfolio, which is offered as evidence of the application of innovation for the degree of Doctor of Engineering.

A brief summary of each submission was given. It was explained that eleven of these submissions relate to a single topic; the analysis and simulation of drivers' steering behaviour. A summary of this project in its entirety was presented. This included a review of existing models of drivers' steering and the results of vehicle tests conducted with a range of drivers. The formulation of a driver model that simulates the steering behaviour exhibited in the tests was then imparted. Then, the way in which this driver model was used to develop a switching strategy for variable dampers was illustrated.

Finally, eight specific illustrations of the way in which this research has applied innovation to the engineering business were communicated.

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